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BRITISH WELDING JOURNAL

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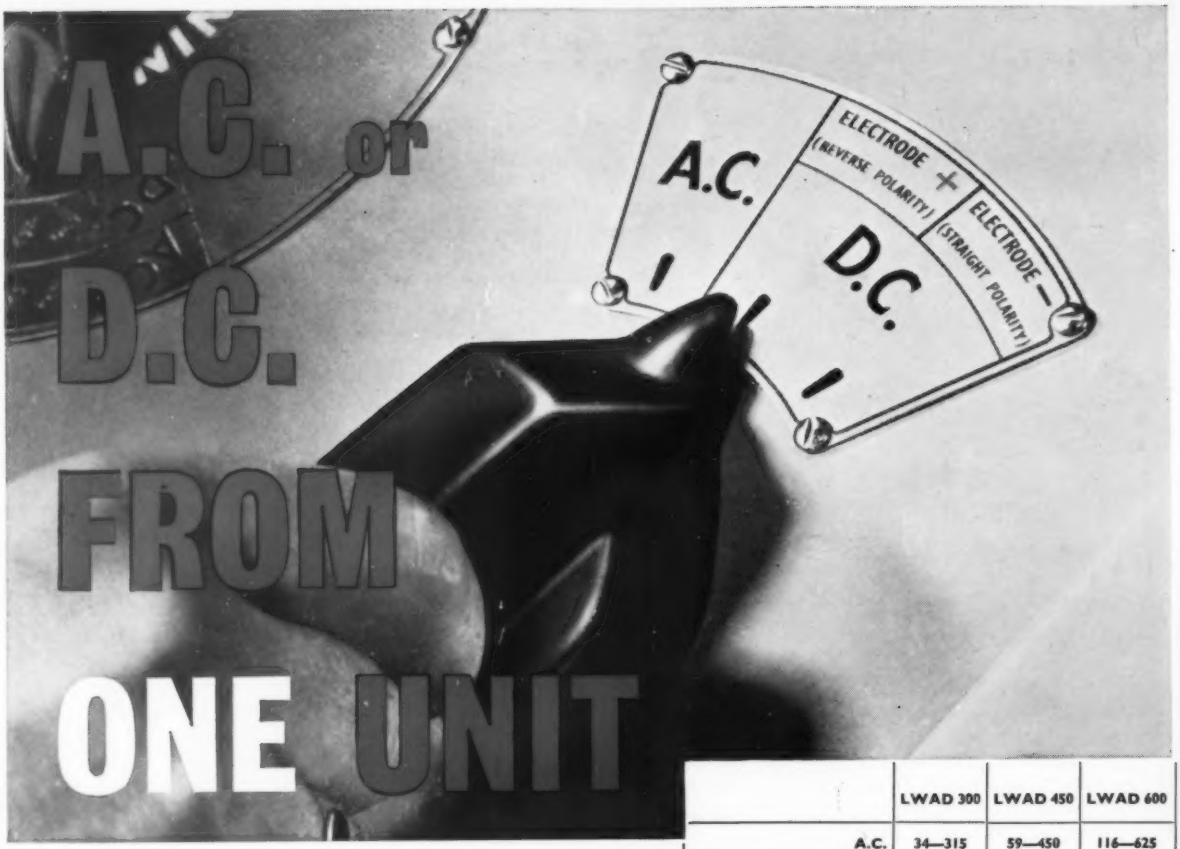

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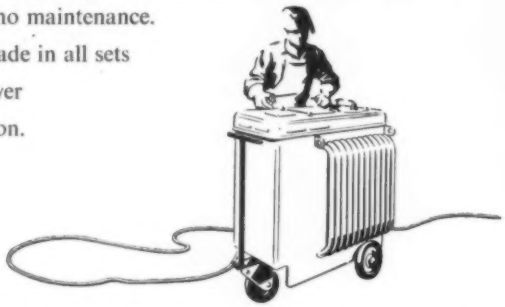

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Inside front cover

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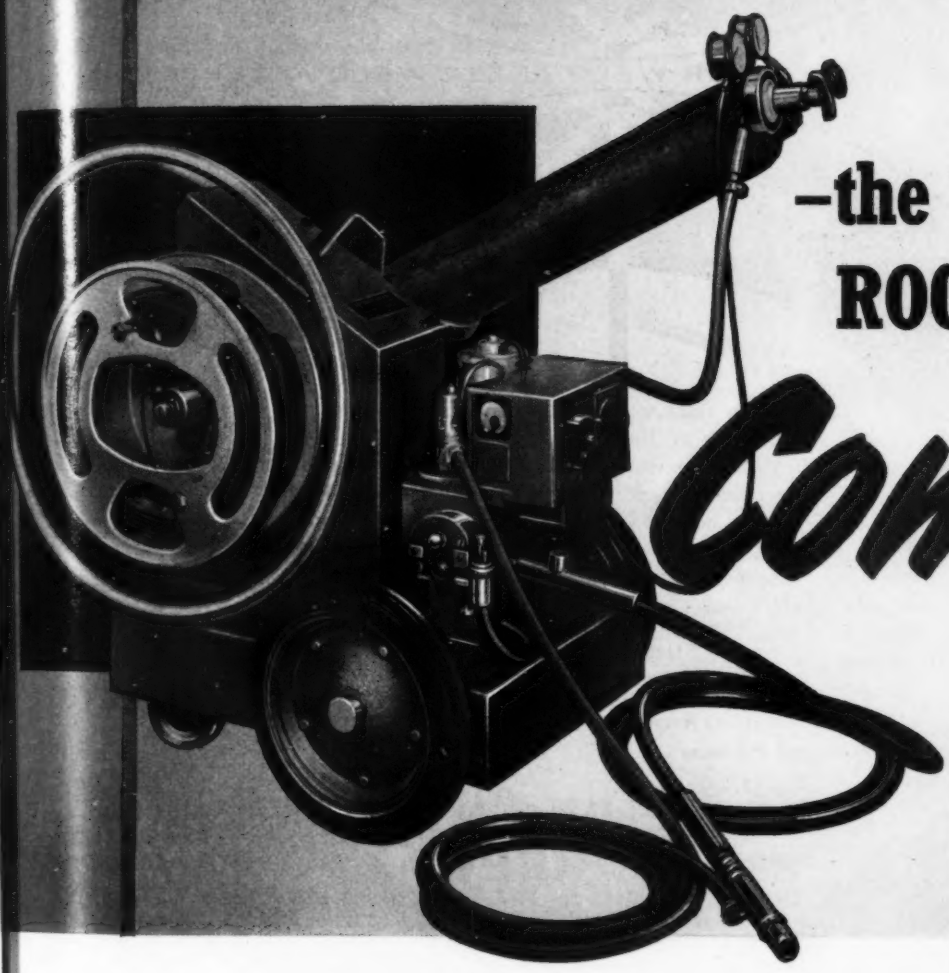

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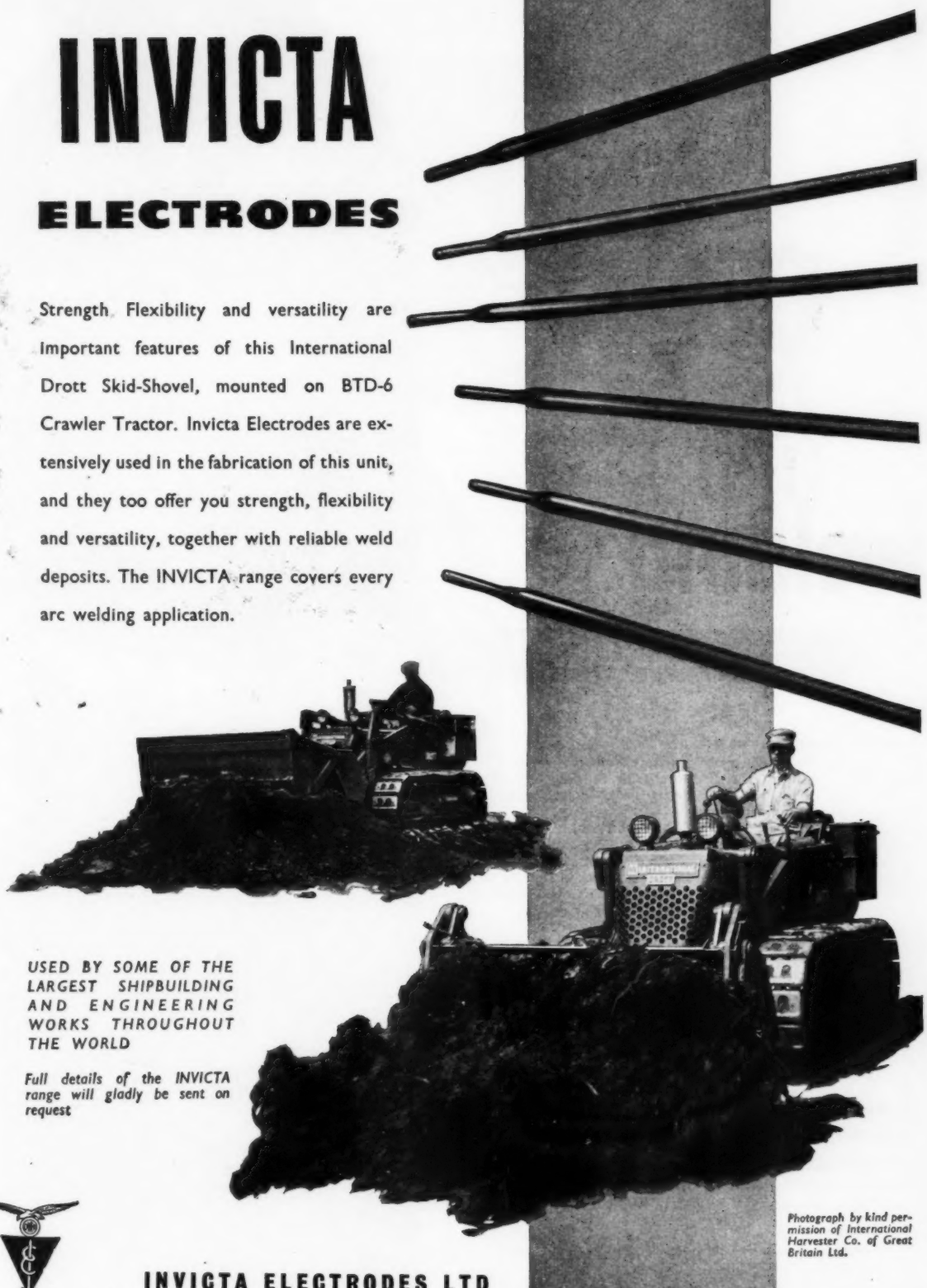

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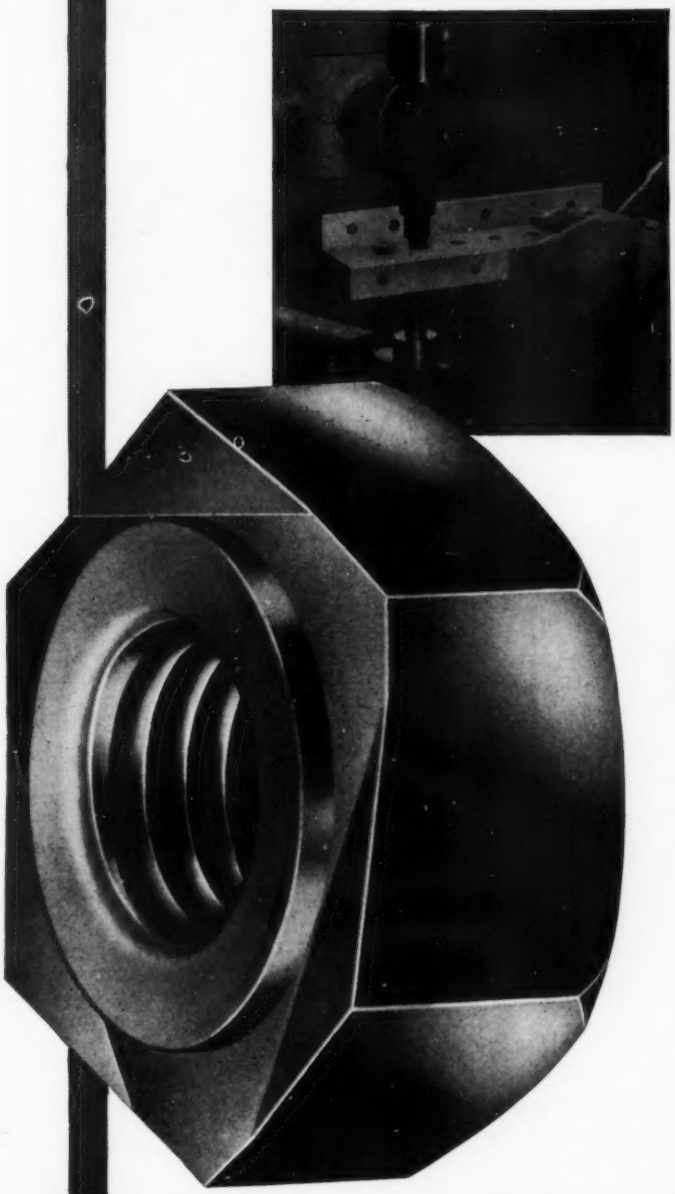

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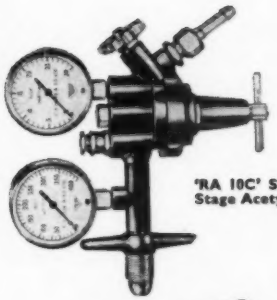

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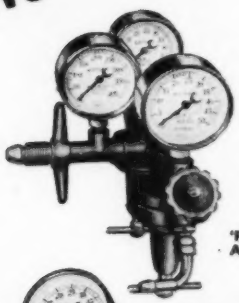

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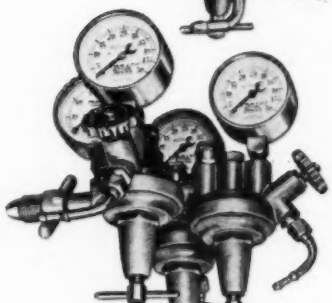

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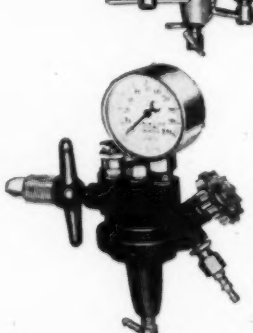

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BK 34A	2400	355	Integral
BK 34B	2400	355	Clamp on
BK 42	600	56	—
BK 42A	600	56	Integral
BK 42B	600	56	Clamp on
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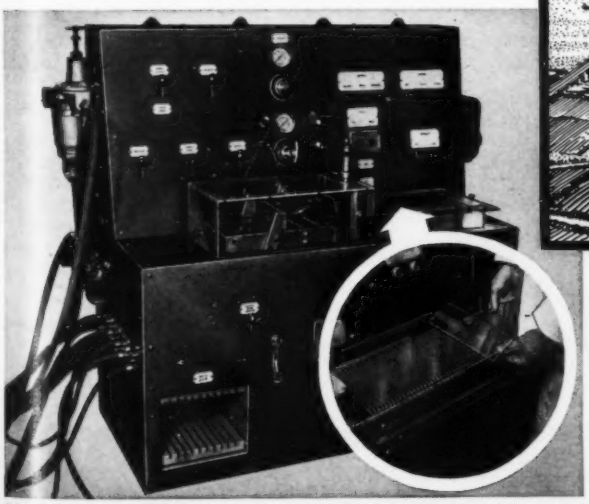

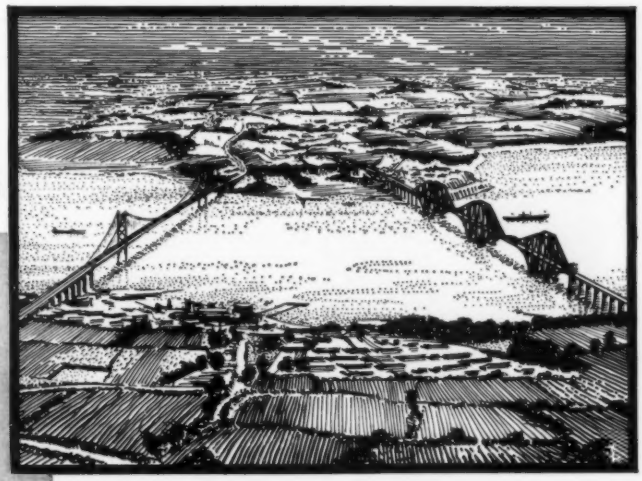

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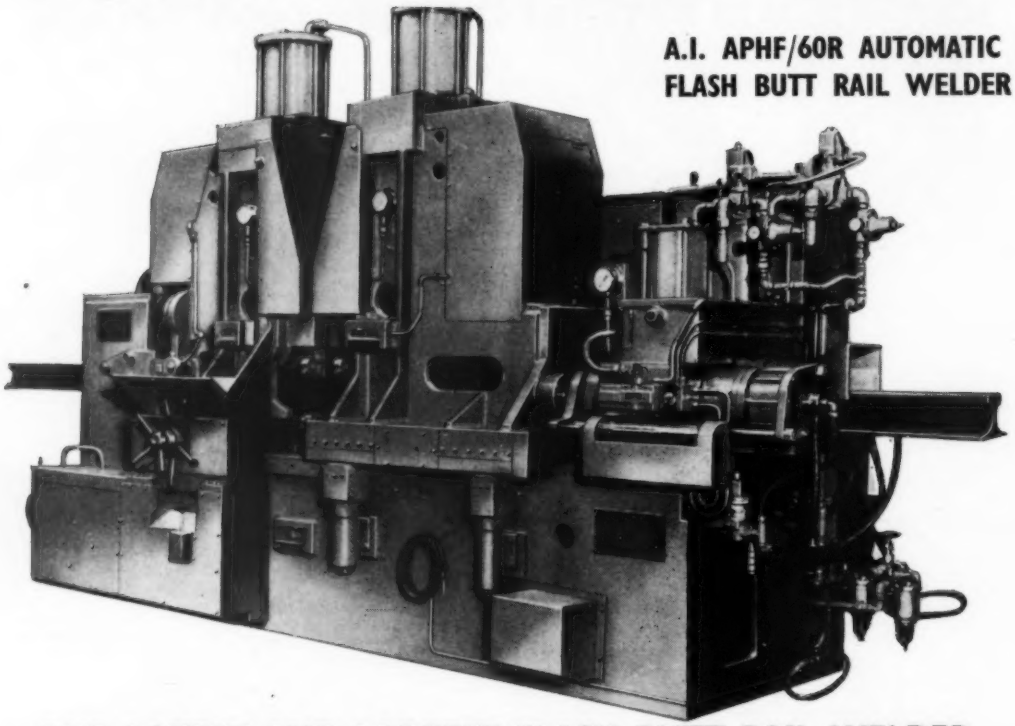

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Welding RESEARCH

B.W.R.A. REPORT

Further Studies of Iron – Oxygen Combustion in Gas Cutting

By A. A. Wells, B.SC.(ENG.), PH.D., A.M.I.MECH.E.

Following an earlier experimental study of combustion produced by transverse flat oxygen jets at the ends of round bars, the present report covers an extension of the work, quantitatively, to plate cutting. The plates used for the tests ranged from ½ in. to 6 in. thick, and a number of cut widths were investigated.

It is shown that the primary function of the preheating flame in oxygen cutting is to maintain an ignition temperature at the top face of the cut, and it is established, inter alia, *that greatest oxygen economy is obtained, on cutting thick material, when cut width × cutting speed (sq.cm/sec) is equal to or less than 4–5 times the thermal diffusivity of the cut material.*

SOME of the physical processes governing the gas cutting operation have been discussed in an earlier report.[1] In particular, it was shown that the heat required to make a cut is primarily that associated with melting the kerf and maintaining by conduction the temperature gradient in surrounding material. By contrast, especially in thick material, radiative and convective losses are quite small. Thus the total heat necessary to make a given cut may be predicted with reasonable accuracy.

In the same report the conditions governing iron and oxygen combustion rates were compared theoretically and experimentally with those of a boundary layer diffusion model, previously applied to other combustion examples. Oxygen and iron impurity effects were taken into account thereby. On the other hand, the combustion system studied was one-dimensional, requiring no simultaneous preheat flame, but not giving boundary layer thicknesses comparable with those in plate cutting. Provided that the boundary layer thickness could be measured independently through the use of a heat transfer analogy the correct prediction of combustion rates was possible, but the aerodynamics of the apparently simple one-dimensional system proved to be complex.

To make further progress it was therefore necessary to devise (i) an experimental system whereby iron–oxygen combustion rates could be measured accurately in plate cutting; and (ii) an aerodynamic model to permit calculation of boundary layer thicknesses in the same example. For the latter purpose a first comparison would obviously be made with well documented results relating to friction and heat transfer in pipe flow.

Exploratory Work

It has already been noted that the total heat to make a parallel sided cut in plate may be computed with sufficient accuracy for use in a heat balance. Additionally, if necessary, this heat could be measured calorimetrically, although this might be difficult to do with precision. Thus, in an experimental study of superficial iron–oxygen combustion rates in plate cutting, it would be required either to measure the independent contribution from the preheating flame or to do

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with-out preheat altogether. Exploratory work was directed to both these ends. Thus, in reference,[2] careful determinations of oxygen cutting preheat flame heat transfer efficiency are described. It was found calorimetrically that such a flame traversing a plain plate so as to cause a heated spot transferred from 60 to 75% of combustion heat to the plate. However, if the traverse speed were dropped, the former value decreased appreciably, owing to intensified surface heat losses from the hotter plate. Furthermore, these experiments were necessarily performed without a cutting oxygen jet or a cut slot. When simulating the latter conditions (bearing in mind that actual cutting conditions would not have permitted an efficiency measurement) it was concluded that significant efficiency changes would occur. Thus, despite extensive work, it was concluded that no accurate estimate of preheat flame efficiency would be possible.

The next step was to try to do without the preheat flame in experimental oxygen cutting of furnace preheated plates.[3] Temperatures up to 650°C. were employed, but stable cutting conditions could not be achieved; in particular, there was a tendency for combustion to stop suddenly. Masking effects of scale on the top plate surface were suspected, but no improvement could be obtained either by minimizing scale formation during preheating or by coating the top surface with borax flux to remove scale during cutting. It was noted, however, that stable cutting conditions could be maintained with very much smaller preheat flames than would be required with plates initially at room temperature; in fact all that was necessary was to bleed a small quantity of acetylene from the preheating jet—no flame could be seen.

At this stage it was thought that the preheating flame might fulfil some catalytic function apart from maintaining an ignition temperature at the top of the cut. It was therefore decided to attempt cuts using a high-frequency induction heater to produce the top surface preheat. This was conveniently possible on mild steel bars 1 in. wide × $\frac{3}{8}$ in. thick in a 6kW heater, using as a concentrator an expendable 0·1 in. dia. straight mild steel welding wire laid along the top surface in the path of the intended cut. In this arrangement a cylindrical heating coil was used, coaxial with, and enveloping the bar. Stable cuts could be maintained with the main bar at about 600°C., the concentrator wire at above 1000°C. as estimated from colour, and a cutting orifice diameter normal for $\frac{3}{8}$ in. thick material. On the other hand, there appeared to be no accurate means for assessing the major heat contribution at the bar from the h.f. source, and there was a further disadvantage, common to the preheated plate experiments, in that the fused metal tended to congeal at the bottom of the cut, making difficult a later estimate of kerf width. This arrangement was abandoned for these reasons.

Discussion of Exploratory Results

In the experiments previously described[1] and mentioned in the foregoing, the following features appear:

(*a*) A combustion face can be maintained across the flat diametral face of a round steel bar initially at room temperature without a preheat flame, if the bar is slowly rotated continually to present fresh hot metal to the line of impact of the flattened oxygen jet

(*b*) A parallel sided cut in plate may be maintained by means of a traversed oxygen jet if (i) the plate is uniformly preheated to 600°C. or more; and (ii) a small amount of acetylene is bled concentrically to the oxygen jet at its periphery at the top of the plate, or a region immediately adjacent to the jet is preheated to 1000°C. or more by electromagnetic induction.

The assistance arising from having the steel plate (as distinct from the bar) at a reasonably high uniform preheat temperature may be understood when it is recognized from the heat conduction conditions that combustion rates (cal/sq.cm sec) for comparable ambient temperatures must be at least twice as great in the former case, there being conduction losses to neutralize in the plate which do not arise in the bar burning case.

On the other hand, an ancillary means of maintaining an ignition or combustion temperature at the position of first impact of the oxygen jet appeared to be absolutely necessary in all the instances examined, although it took three quite different forms. No precise temperature value could be given, but it was clearly greater than 650°C., and in two of the three examples was reached without the use of an additional fuel gas. It was concluded that:

(*a*) The preheating flame serves to maintain an ignition temperature rather than to assist the combustion catalytically

(*b*) Although in certain instances it may supply an appreciable fraction of the total heat involved in the cutting operation, this is not an essential feature.

These conclusions also appear to be relevant to oxygen cutting of titanium, which has recently been studied.[6] In spite of the much larger cutting speeds possible with this material it was not possible to dispense altogether with a preheating flame in experiments where this was attempted.

The congealing of fused metal at the bottom of the cut with steel plates having a high general level of preheat has previously been noted by Morelle,[4] who also drew attention to the increased iron contents of slags as cutting speeds increased in these and other cases. These effects are inter-related and explicable. As the general preheat temperature increases, the heat of melting decreases, but the combustion heat for the same mass (or volume) is maintained. Thus more material may be melted for combustion of a given quantity, other things being equal. Furthermore, as cutting speeds increase, less heat is conducted away for unit cut volume (equation 2, reference 1) giving a supplementary effect. It is likely that the congealing effect is more noticeable for another reason; namely, that with a generally preheated plate or an increased cutting speed the melted zone will be elongated backwards, so that the molten metal has a better chance of escaping backwards behind the jet instead of being swept out. The elongated molten pool is a common feature in fusion welding, particularly at the higher speeds in submerged-arc welding, and has been discussed from the heat flow aspect by the present author.[5]

With these results in mind it was decided to re-examine specimens initially at room temperature. The

intention was to reduce the oxy-acetylene preheat flame to the lowest intensity required to maintain stable combustion and so to reduce to the minimum level its contribution to total heat. Thus, errors in computing combustion rates, resulting from inaccurate estimation of preheat flame heat transfer efficiency, would be minimized.

Theory

It has been shown[1] that the primary heat requirement of plate cut by means of an oxygen jet is that necessary to melt the kerf together with that conducted away in the plate. In comparison, the surface losses from radiation and air convection may be shown as sufficiently small to be neglected.

Thus, the heat to be supplied for unit thickness of plate (equation 1 of reference 1) is:

$$Q = 8kT\left(\frac{1}{5}+\frac{vd}{4a}\right) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where k is thermal conductivity, a thermal diffusivity$=k/\rho c$, ρ is density, c is specific heat, and T is the melting (or combustion face) temperature above the surroundings, v is the cutting speed and d is the cut width.

For a cut of given width and speed the total heat per unit thickness may thus be readily estimated, using values given in reference 1 and:

$T = 1500°C.$ $\quad c = 0{\cdot}155$ g cal °C.
$k = 0{\cdot}10$ cal/°C.cm sec $\quad a = 0{\cdot}082$ sq.cm/sec
$\rho = 7{\cdot}86$ g/cu.cm

Any contribution from the preheating flame to be deducted from the total heat may be estimated from the mass flow rates of heating oxygen and fuel gas, together with the appropriate measured value of the heat transfer efficiency. Since the preheating flame is invariably fuel-rich in order to maintain stability it may reasonably be assumed that the heating oxygen is completely burned, as a result of which the approximate calorific value 4,000 cal/g of oxygen may be used.

It has been shown[2] that an appropriate value for the heat transfer efficiency would be 0·77. Thus the preheat contribution per unit of thickness to be deducted from the total heat should be:

$$q = 3080\frac{m}{L} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where m is the heating oxygen flow rate and L is plate thickness.

It is further shown (reference 1, equation 6) that the combustion rate between oxygen and iron per unit area of combustion surface is given by the diffusion relationship, after substituting appropriate physical constants, as:

$$q'' = \frac{3{\cdot}58}{x}\log_e\frac{1}{\eta} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where x is boundary layer thickness (cm) and η is the equivalent fractional gaseous impurity of the oxygen.

The latter is extensively discussed in reference 1; for 99·7% oxygen purity and a 0·2% C steel, with oxidation to Fe_3O_4, η would be shown to be 0·0154.

For the present purpose it may be assumed that combustion takes place on an area $\pi d/2$ for unit plate thickness, where this is half the peripheral area of the oxygen jet. By combination of equations (1), (2) and (3) an estimate of the mean boundary layer thickness taken over the whole depth of the plate may be made for the purpose of comparison with a calculated boundary layer thickness to be determined by analogy with fluid friction or heat or mass transfer in other cases of pipe flow. Thus:

$$8kT\left(\frac{1}{5}+\frac{vd}{4a}\right)-3080\frac{m}{L}=\frac{\pi d}{2}\cdot\frac{3{\cdot}58}{x}\log_e\frac{1}{\eta} \quad \ldots\ldots \quad (4)$$

and, inserting appropriate numerical values:

$$1200\left(\frac{1}{5}+\frac{vd}{4a}\right)-3080\frac{m}{L}=\frac{d}{x}\times 23{\cdot}5$$

In the former respect the paper by Kaye, Toong and Shoulberg[7] is of direct interest, since it is concerned with fluid friction and heat transfer for subsonic and supersonic gas flow at a pipe entry. The extensive results of these investigators lead them to suggest that valid comparison may be made between the conditions stated and those obtaining for the lamina boundary layer along a flat plate placed parallel to an undisturbed gas stream. For these conditions and an incompressible flow the Blasius relationship holds:[8]

$$\frac{d}{x}=\frac{1}{5{\cdot}2}\frac{d}{l}\sqrt{\left(\frac{ul\rho}{\mu}\right)} \quad \ldots\ldots\ldots\ldots \quad (5)$$

where l is the distance from the leading edge, u is the main stream velocity, ρ is the gas density, and μ the viscosity appropriate to the boundary layer.

Here the quantity $ul\rho/\mu$ is a Reynold's number; in computation, convenient use may be made of the mass flow per unit area at the nozzle, which is itself equal to $u\rho$.

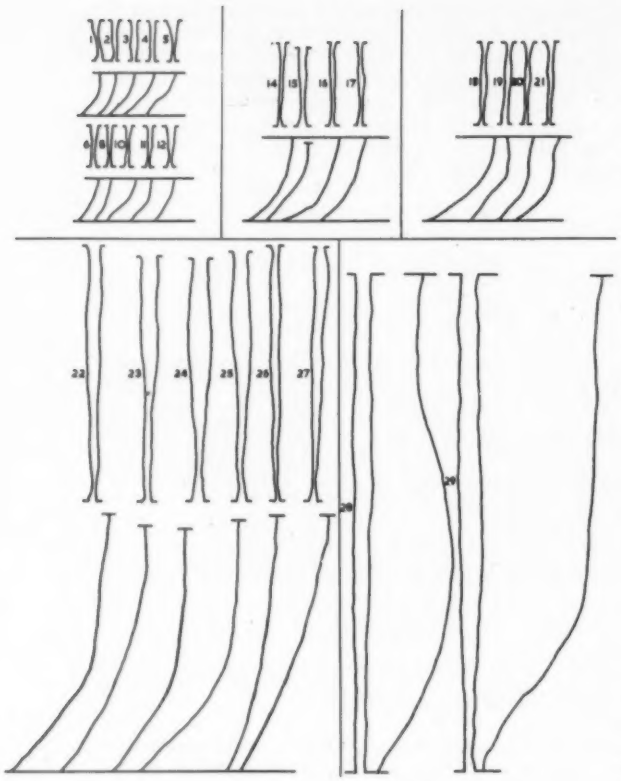
For compressible flow the boundary layer thickness is increased, according to Howarth,[9] by the factor $1+0{\cdot}2\,(\gamma-1)M^2_c$, where γ is the specific heat ratio and M is the local Mach number appropriate to the main stream flow. It will be seen that this correction is comparatively small for all except high Mach numbers, which would not obtain in gas cutting except at very high cutting oxygen pressures; in subsequent work it is proposed to neglect this correction.

The boundary layer thickness of equation (5) is that with reference to any distance l along the pipe or flat plate. For combustion rate calculations dealing with total plate thickness L, a mean effective boundary layer thickness is required which may be shown by integration to be half the value above, if the quantity L be substituted for l.

For the purpose of comparison with experiments it is appropriate to plot the quantity $L/x=d/x.L/d$ against the Reynold's number $uL\rho/\mu$, using d either as the cut width or nozzle diameter and the quantity d/x from equation (4).

Experiments

In early trials it was found that satisfactory cuts could be made in mild steel plates $\frac{1}{2}$ in. thick and upwards with preheat flames (using acetylene as the preheating gas) sufficiently small to contribute $\frac{1}{3}$ or less of the total heat. Under these conditions combustion stability could be maintained, and a maximum



1—*Profiles of experimental cuts*

permissible cutting speed for given oxygen pressure could be determined with relation either to definite drag length or to the point at which the cut ceased to penetrate fully through the plate. To bear relation to the maximum combustion rate for any given set of conditions it was therefore decided to characterize the critical cutting speed using a moderately high ratio of drag length to plate thickness. Thus, when a cut had been satisfactorily started the cutting speed would be increased in steps, care being taken to cut a sufficient length at each speed to establish steady conditions. On later examination of the cut surface the critical cutting speed for the condition of the combustion experiments could be determined by inspection.

Experimental cuts were made down the centres of bars of limited width so as to facilitate the micrometer measurement of cut widths, using a previously measured bar width and the thicknesses of the cut halves as data. This, incidentally, led to economy in the use of material, considerable amounts of which were in any case required, especially in the larger thicknesses. Under the conditions described it was important first to establish that no difference in total heat would be introduced as between the bar of limited width and the infinite plate, for which the theoretical heat conduction conditions were established in equation (1). This matter has been extensively studied[10] and it is shown that the finite plate width influences only the temperature to which the bar equalizes at some distance behind the heat source (oxygen jet),

Table I

Material compositions

Thickness, cm	*C, %*	*Mn, %*	*Si, %*	*S, %*	*P, %*
1·275	0·22	0·56	0·01	0·049	0·036
2·53	0·18	0·75	0·02	0·052	0·021
7·62	0·16	1·01	0·14	0·032	0·04
15·2					

whereas the temperature distribution in the plate immediately surrounding the jet is negligibly disturbed from that in the infinite plate. Nevertheless, care was taken to use bars of sufficient widths, which varied from 1 in. in the case of ½ in. thickness to 2 in. for 6 in. thickness.

Oxygen of standard 99·7% purity was used. Chemical compositions, especially with regard to carbon, sulphur and phosphorus were also determined for each material employed, and are given in Table I. Plain cylindrical cutting oxygen nozzles were used, of standard pattern with surrounding preheating jets, except that in certain instances the cutting orifices were drilled over-size so as to standardize on the size of preheating jet throughout the experiments. Cutting jet height above the plate surface was maintained at 4 mm. Arrangements for the independent measurement of mass flow rates for acetylene, heating, and cutting oxygen respectively[8] involved the use of standard circular orifice plates across which pressure differences are registered by means of open-limb manometers, whereas absolute pressures on one side of each orifice are measured by means of closed-limb manometer. For the sake of convenience in the present case, the cutting oxygen was measured as a difference between total and heating oxygen.

The cutting head for these experiments was mounted on a standard tractor, with provision both for speed variation and governing, and the measured tractor speeds were checked by direct calibration at the end of each experiment.

Results

To achieve a sufficiently wide variation of conditions for study, cuts were made in plates ½, 1, 3, and 6 in. thick, and in the ½ in. and 3 in. plates two alternative nozzle diameters were employed. In every case results for several cutting oxygen pressures at constant preheat were obtained. The results are collected in Table II, and longitudinal and transverse cut profiles appropriate to the chosen critical conditions are shown in Fig. 1. This diagram shows that the necessity to reduce preheat and, at the same time, to increase cutting speed to approach some positive limit for the determination of limiting combustion rate, impairs to some extent the accuracy of profile obtained. These cuts should not therefore be construed as in any way representative of good practice; their purpose is purely that of combustion study.

The values of $vd/4\alpha$ in Table II have been computed on the basis of nozzle diameter d, and not on cut width. Since d enters both sides of equation (4) the ultimate result is not unduly sensitive to absolute values.

Table II

Collected results

No.	Plate Thickness, cm	Orifice Dia., (d) cm	Preheat Oxygen, g/sec	Cutting Oxygen, g/sec	Cutting Speed, (v) cm/sec	Cut Width, (d) cm	$\frac{vd}{4\alpha}$	Total Heat, cal/cm sec	Combustion Heat, Preheat, cal/cm sec	Combustion Heat, cal/cm sec	$\frac{d}{x}$	$\frac{L}{d}$	$\frac{L}{x}$	$u\rho$	$\frac{uL\rho}{\mu}\times 10^4$	Fractional Cutting Oxygen Utilization	$\frac{\text{Cut sp} \times \text{thick}}{\text{Cut O}_2 \text{ mass flow}}$	$\frac{\text{Preheat Oxygen}}{\text{Cutting Oxygen}}$
1	1·275	0·178	0·046	0·168	0·233	0·167	0·125	390	111	279	11·8	7·2	85	6·74	1·84	0·52	1·76	0·27
2	„	„	0·042	0·206	0·380	0·186	0·204	485	102	383	16·3	„	117	8·25	2·25	0·60	2·36	0·20
3	„	„	0·044	0·310	0·646	0·177	0·346	655	106	549	23·3	„	168	12·45	3·39	0·56	2·66	0·14
4	„	„	0·050	0·334	0·741	0·231	0·398	716	121	595	25·3	„	182	13·4	3·65	0·56	2·83	0·15
5	„	0·100	0·040	0·124	0·116	0·150	0·035	282	97	185	7·9	12·75	101	14·5	3·95	0·47	1·19	0·32
6	„	„	0·045	0·121	0·148	0·127	0·045	294	109	185	7·9	„	101	15·4	4·20	0·48	1·56	0·37
7	„	„	0·037	0·138	0·180	0·189	0·054	305	89	216	9·2	„	117	17·6	4·80	0·50	1·67	0·27
8	„	„	0·039	0·141	0·210	0·112	0·063	316	94	222	9·4	„	120	18·0	4·90	0·50	1·90	0·28
9	„	„	0·037	0·187	0·423	0·097	0·128	393	90	303	12·9	„	165	23·8	6·50	0·51	2·88	0·20
10	„	„	0·047	0·213	0·423	0·109	0·128	393	114	279	11·8	„	151	27·1	7·38	0·42	2·53	0·22
11	„	„	0·044	0·355	0·561	0·124	0·170	443	106	337	14·3	„	183	45·1	12·3	0·34	2·02	0·12
12	„	„	0·055	0·407	0·720	0·120	0·217	500	133	367	15·6	„	199	51·8	14·1	0·29	2·25	0·14
13	„	„	0·034	0·552	0·720	0·149	0·217	500	82	416	17·7	„	226	70·3	19·2	0·24	1·66	0·06
14	2·53	0·118	0·045	0·281	0·286	0·100	0·102	362	55	307	13·0	21·5	280	25·8	14·0	0·68	2·57	0·16
15	2·43	„	0·054	0·336	0·295	0·145	0·105	366	68	298	12·7	20·6	261	30·8	16·0	0·54	2·13	0·16
16	2·53	„	0·034	0·307	0·317	0·117	0·113	376	41	335	14·2	21·5	305	28·2	15·25	0·68	2·61	0·11
17	„	„	0·047	0·411	0·434	0·105	0·154	425	57	368	15·6	„	335	37·7	20·4	0·57	2·67	0·11
18	„	„	0·049	0·496	0·571	0·095	0·203	483	60	423	18·0	„	387	45·5	24·6	0·54	2·92	0·10
19	„	„	0·056	0·610	0·550	0·106	0·196	475	68	407	17·3	„	372	56·0	30·3	0·42	2·28	0·09
20	„	„	0·044	0·713	0·667	0·119	0·237	523	54	469	20·0	„	430	65·4	35·4	0·42	2·36	0·06
21	„	„	0·042	0·703	0·720	0·119	0·256	547	51	496	21·1	„	453	64·6	34·9	0·45	2·59	0·06
22	7·82	0·264	0·053	0·928	0·211	0·284	0·168	442	21	421	17·9	29·7	532	16·9	28·3	0·89	1·78	0·06
23	7·50	„	0·053	1·335	0·275	0·308	0·219	503	22	481	20·5	28·4	583	24·3	38·9	0·68	1·55	0·04
24	7·35	„	0·049	1·74	0·313	0·317	0·249	539	21	518	22·0	27·8	611	31·7	49·8	0·55	1·32	0·03
25	7·62	„	0·050	2·39	0·392	0·346	0·312	615	20	595	25·3	28·8	730	43·6	71·0	0·47	1·25	0·02
26	7·82	0·178	0·047	1·00	0·196	0·180	0·105	366	18	348	14·8	43·9	650	40·2	67·2	0·68	1·53	0·05
27	„	„	0·044	1·46	0·338	0·170	0·181	457	17	440	18·7	„	822	58·5	98·0	0·59	1·82	0·03
28	15·2	0·325	0·068	3·54	0·360	0·343	0·352	662	14	648	27·5	46·7	1280	42·8	139	0·70	1·55	0·02
29	„	„	0·057	4·38	0·439	0·389	0·430	756	12	744	31·7	„	1480	52·9	172	0·64	1·52	0·01

Whereas nozzle diameter is well defined, cut width is not, and measurement of its average value implies use of certain conventions which it would be desirable to avoid. In fact, the results have also been analysed on a basis of cut width rather than nozzle diameter; the form of correlation obtained is unchanged, but scatter is greater. The latter results have not been presented in this report. The combustion heat for unit thickness in Table II is taken as the difference between total heat for unit plate thickness and preheat averaged over the whole thickness. With the degree of accuracy of measurement obtainable, no more elaborate treatment differentiating cut width effects or preheat or boundary layer thickness distributions through the plate thickness was thought to be feasible. For the sake of consistency the quantities L/d in Table II are also in terms of nozzle diameter rather than cut width.

The quantity 'fractional cutting oxygen utilization' in Table II is computed from the combustion heat and the cutting oxygen mass flow rate (divided by plate thickness) converted into potential heat at 4,000 cal/g of oxygen. The other index of efficiency given in the table, namely (cut speed $\times$ plate thickness)/(cutting oxygen mass flow rate) in sq.cm/g is useful empirically but neglects the fact that cuts must be wider in thick material and also neglects heat conduction effects.

Reynold's number $uL\rho/\mu$ is plotted against the ratio L/x in Fig. 2, together with the Blasius line derived from equation (5). In the Reynold's number the quantity u is oxygen velocity, ρ is density ($u\rho$ is mass flow per unit area at the nozzle) and μ is the viscosity, taken to be $4{\cdot}68 \times 10^{-4}$ c.g.s. at 1000°K.

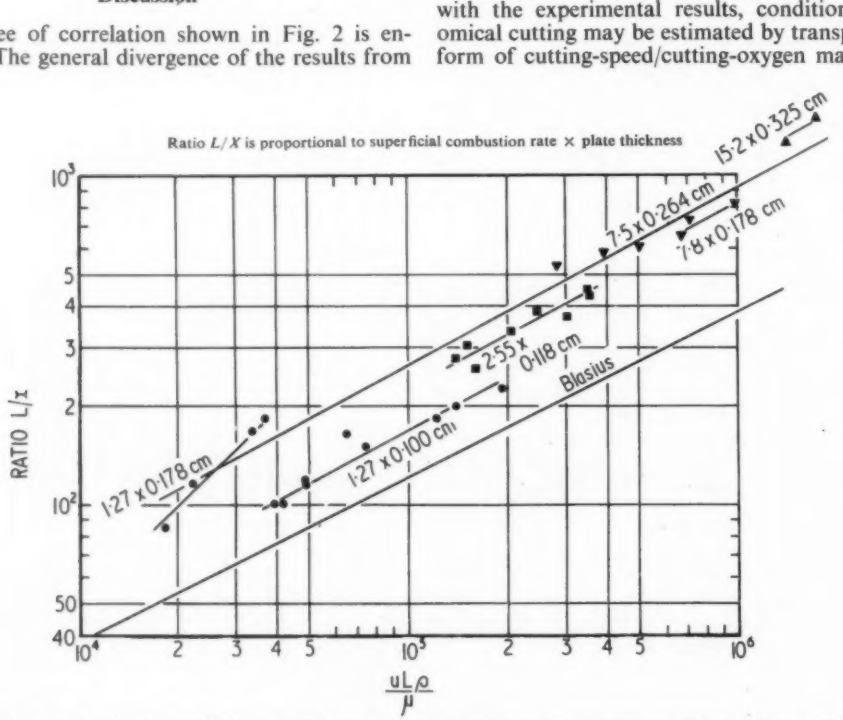
Discussion

The degree of correlation shown in Fig. 2 is encouraging. The general divergence of the results from the Blasius line is not regarded as important, since several of the constants in equation (4) are not determinable with precision. For instance it is not entirely clear that the combustion periphery should be $\pi d/2$; a greater value might be possible. The computed diffusion constant, viscosity and impurity of the oxygen are also susceptible to error, bearing in mind the uncertain boundary layer temperature (taken as 1000°K) and impurity composition.

It is also interesting to note that the divergence from a datum line parallel to the Blasius line follows a fairly regular pattern, particularly with respect to the absolute value of nozzle diameter. Similarly, there are apparent links between this divergence and (i) the ratio preheating/cutting-oxygen mass flow rates; (ii) proportion of cutting oxygen computed as absorbed in combustion with iron in the cut; and (iii) the factor $vd/4\alpha$. It would be valuable to establish reasons for such behaviour.

The cuts in the thick plate took place at a very high ratio of L/d, generally coincident with high cutting oxygen utilization. In fact it would appear that the latter is overriding, whereas it might have been anticipated that a limit would be set simply by exhaustion of the kinetic energy of the cutting oxygen stream from friction. The question may therefore be asked as to why cuts in thin plate may not be made at such high L/d ratios. It is certain that, under the conditions of the experiments, use of the 0·10 cm dia. nozzle on $\frac{1}{2}$ in. plate offered no advantage, with either of the possible criteria, oxygen utilization or cut-speed/oxygen mass flow rate, as compared with use of the 0·178 cm dia. nozzle.

Finally, since equation (4) may be said to correlate with the experimental results, conditions for economical cutting may be estimated by transposing in the form of cutting-speed/cutting-oxygen mass flow rate.



2—Combustion boundary layer thicknesses and oxygen flow Reynold's numbers for oxygen cuts with plate thicknesses L

Table III

Recommended oxy-acetylene cutting conditions[11]

Plate Thickness cm	*Nozzle Dia., cm*	*Preheat Oxygen,* g/sec*	*Cutting Oxygen, g/sec*	*Cutting Speed, cm/sec*	$\frac{vd}{4\alpha}$
1·27	0·100	0·129	0·40	0·59	0·18
2·54	0·118	0·177	0·78	0·47	0·17
7·62	0·178	0·257	2·52	0·34	0·18
15·2	0·193	0·322	4·18	0·25	0·15

* On the basis 1 vol C_2H_2/1·5 vols O_2.

Differentiating with respect to the latter quantity and equating to zero, we have:

$$A+B\left(\frac{vd}{4\alpha}\right)=C\frac{d}{x}=C\frac{d}{L}\cdot\frac{L}{x}=C\frac{d}{L}\sqrt{\left(\frac{uL\rho}{\mu}\right)}=C\sqrt{\left(\frac{ud^2\rho}{\mu L}\right)}\quad..(6)$$

Put $\frac{vd}{4\alpha}=y$, $\frac{ud^2\rho}{\mu L}=x$

then

$$A+By=C\sqrt{x},\ y/x=\frac{C\sqrt{x}-A}{Bx}$$

and $\frac{d(u/x)}{dx}=0$ when $C\sqrt{x}=2A$, and $y=A/B$

This leads to the simple result from equation (4) (under conditions where preheat provides a negligible supplement to combustion heat), that the most economical use of cutting oxygen is achieved when $vd/4\alpha=\frac{1}{8}$. Where preheat is significant the optimum value will be lower. Similarly, there should be an optimum cutting-oxygen mass flow rate per unit plate thickness at this value of $vd/4\alpha$. These results are, in general, supported by each of the groups of experiments, although the data are not sufficiently accurate for positive optimum correlation to be seen. If L/d could be maintained at a constant limiting value, irrespective of plate thickness, the theoretical result shown above would imply diminishing oxygen velocities (hence pressures) with greater thicknesses.

It is also interesting to compare the conditions of the experiments with recommended values given by Seymour-Semper.[11] These are given in Table III in the units of this paper. The most striking feature is the proximity of the recommended values of $vd/4\alpha$ to the value already deduced. In contrast, the recommended preheat rates are three to six times greater than those used for the special conditions of these experiments. Recommended cutting-oxygen mass flow rates are somewhat greater, but the cutting speeds are of the same order as those which arose from the experiments. Some degree of comparison may, therefore, be permitted between the deductions of this investigation and industrial gas cutting. The most important of these, if it could be substantiated, is that cutting speeds on plates up to about 1 in. thick would be markedly increased if the low combustion rate in this case could be understood and avoided.

On the question of optimum cutting conditions a qualification is necessary that efficient use of oxygen may not always be a suitable criterion. It is certainly not likely to be so with an expensive metal like titanium, where much larger values of $vd/4\alpha$ than $\frac{1}{8}$ are obtainable, in view of the physical and chemical conditions. In such a case a more suitable criterion would be cut and heat-affected zone width, and the latter would be smallest with $vd/4\alpha$ approaching unity, together with the smallest possible cutting jet diameter for given thickness.

Conclusions

1. By using three different methods of surface heating it has been confirmed that the primary function of a preheat flame in gas cutting is to maintain an ignition temperature at the top face of the cut.

2. In gas cutting tests with cylindrical oxygen jets on mild steel bars, using the smallest preheat flames compatible with cutting stability, it has been shown that the gas diffusion mechanism, using boundary layer thicknesses as computed for a flat plate placed parallel to a gas stream, gives combustion rates comparable with those measured. Under these conditions combustion rate is proportional to the square root of cutting oxygen mass flow rate, if each is related to unit plate thickness.

3. On the basis of conclusion 2, combustion rates were lower for plates of small thickness, where a high ratio preheat/cutting-oxygen mass flow rate obtained.

4. The analysis shows that the quantity (cutting speed × nozzle diameter) should be 0·8 times the thermal diffusivity of the plate material for optimum use of oxygen in cutting. This is broadly in agreement with the experimental results and with recommended gas cutting conditions over a range of cut thicknesses.

5. The large values of the ratio plate-thickness/nozzle-diameter realized for cutting thick plates seem only to be limited by exhaustion of oxygen in the cut.

Acknowledgments

Much of the preparatory work leading to the experiments described in this report was performed by Mr. G. Coates before leaving B.W.R.A.; the experimental work was entirely carried out by Mr. M. Frost, and thanks are expressed to both colleagues.

Opinions in this report are the responsibility of the author alone.

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B.W.R.A. REPORT

By A. A. Wells, B.SC.(ENG.), PH.D., A.M.I.MECH.E.

Oxygen Cutting

REPORT ON RESEARCH WORK FOR THE A. 4 (FM. 10) COMMITTEE 1950–1959

In September 1950 the Research Board of B.W.R.A. selected oxygen cutting as a topic for investigation, and a committee was set up under the Chairmanship of Professor O. A. Saunders to study this subject. The boundary layer mechanism for gas–metal combustion was chosen as the most profitable field for study. In outlining the boundary layer theory, the present report describes experiments carried out to check its validity and gives details of observations on ignition temperatures and flame heat transfer efficiencies. Consideration is also given to the extent to which oxygen cutting could be applied to metals other than iron, and brief reference is made to the possibility of using the halogen gases as a means of cutting metals.

Foreword

Towards the end of 1950 B.W.R.A. set up a Committee with the following terms of reference:

> "To study the fundamental aspects of oxygen cutting primarily as a method of preparing plate for welding, with a view to finding whether any improvement can be made in the economy of the process or in the quality of the result."

At the time this was a bold step, partly because it involved B.W.R.A. in research on cutting, and partly because the intention was to carry out a research of an unusual fundamental character.

B.W.R.A. were able to obtain the services of Professor O. A. Saunders as the Chairman of this Committee until he resigned in 1956, and a number of other distinguished practical and academic people sat on this Committee. Dr. A. A. Wells led the investigation throughout.

It later became apparent that the limitation "primarily as a method of preparing plate for welding" should be removed, and it was also found that useful scientific information could be obtained by working on metals other than mild steel, which was the original intention.

By April 1958 it was decided that the original objective had been substantially achieved. It was agreed that the results should be collated and circulated to members.

It is the hope of the Research Board that those interested in cutting will find that this report enables them to obtain a better understanding of what happens during oxygen cutting and, further, that they can apply the results in their practical operations.

Introduction

DURING the 1930s the results of a number of investigations were published,[1,2] whereby accurate assessments of cut width, cutting speed, nozzle diameter, oxygen pressure, and flow rate and fuel-gas flow rate were made for various steel plate thicknesses. These investigations helped considerably in the selection of optimum conditions for making straight cuts on plates. During this period it had also been ascertained that oxygen cuts made under machine controlled conditions were suitable as preparation for welding, since the small surface layer, rich in carbon, and hardened by cooling, was removed in all cases by the welding operation. During the production expansion of the second World War extensive use was made of machine oxygen cutting for weld preparation.

Although the process was well established in 1950, there were at least two variables in oxygen cutting of steel worthy of further examination; namely, the purity of the oxygen used for cutting and the shape of the oxygen nozzle. The state of understanding regarding these matters is well reviewed by Spraragen and Claussen[3] for 1939. Until that time it had been customary to use plain cylindrical nozzles and oxygen of approx. 99·5% purity, this figure presumably being related to the economics of oxygen production.

At its first meeting the Committee considered a specially prepared survey, together with a report on the more recent development work which had been

Report A4/4/59 of the British Welding Research Association, circulated to members in July 1960.

Dr. Wells is Assistant Director of Research (Engineering) of the Association.

undertaken with equipment for producing multiple bevels for plate butt welding. At the same meeting it was noted from the investigator's survey that very little previous work had been conducted on the mechanism of iron and oxygen combustion (on which the process of cutting depended), although there was ample reference to the mechanism of solid phase combustion in the general literature. In particular, the boundary-layer mechanism offered a hypothesis to explain the influence of oxygen purity on the consumption of gas in cutting and on cutting speeds, and a tentative theory for the gas cutting case was presented in the survey. It was decided that this would be the most profitable field for experimental investigation.

Heat Flow by Metal Conduction in Oxygen Cutting

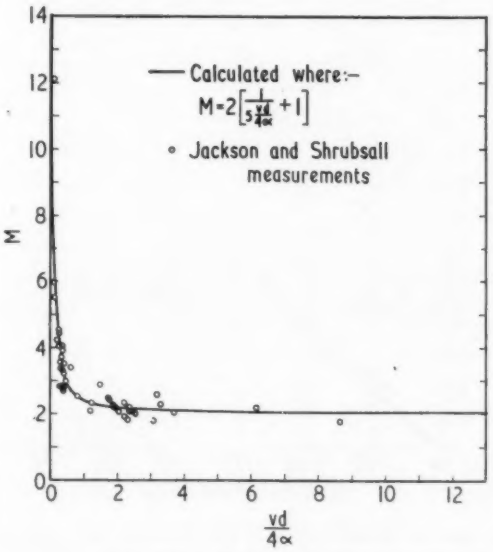
To assess the heat input required to produce a cut of given width and speed, it was recognized that a quantitative study of heat flow by metallic conduction would be needed. Similarly, estimations of the heat lost by radiation and convection would be required, but it could be shown that upper limits for heat transfer by the two latter processes were a whole order less than for metallic conduction.

Mathematical theory for the heat conduction from a line source in an infinite solid had been given independently by Roberts[4] and Rosenthal[5] for materials with thermal properties invariant with temperature. In both oxygen cutting and welding an important consideration is the maximum width of an isotherm (in the direction normal to source travel) for a given temperature, since the isotherm for melting defines the width of either the cut or the weld. The Roberts' solution was therefore transposed to give the maximum isotherm width and this permitted the development of a simple approximate expression which has been widely used since:*

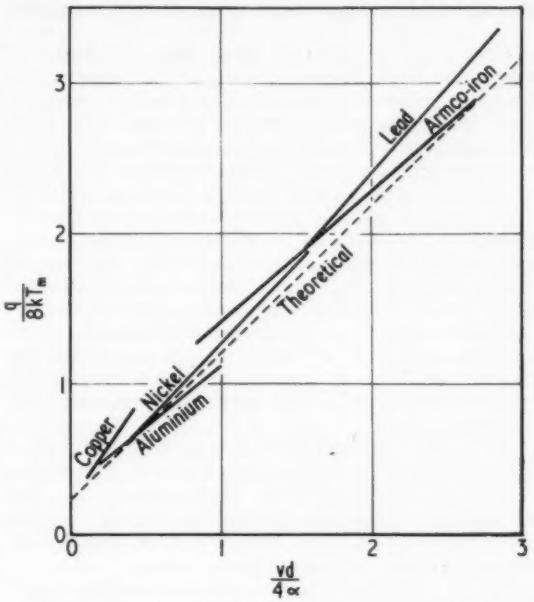
$$q = 8kT\left(\frac{vd}{4a}+\frac{1}{5}\right) \quad \left(\text{for}\ \frac{vd}{4a} > 0{\cdot}1\right) \quad \ldots\ldots\ldots \quad (1)$$

where q = heat input rate for unit thickness, cal/sec.cm
k = thermal conductivity, cal/sec.sq.cm °C.cm
v = source velocity, cm/sec
d = maximum width of isotherm at temperature T above surroundings, cm
a = thermal diffusivity, sq.cm/sec
$= k/\rho c$, where ρ is density and c is specific heat.

* A similar expression, omitting the $\frac{1}{5}$ term, was developed independently at about the same time by N. N. Rykalin.



1—*Butt welding heat dissipation*



2—*Superimposed results of Apps and Milner[8] analysed non-dimensionally with latent and specific heat combinations*

Experimental confirmation was obtained by comparison with measurements published in the U.S.A.,[6] and this work was embodied by the investigators in a report also published in America[7] (Fig. 1). At this time also, the relation between isotherm shape and heat input rate in welding was recognized, so permitting the link to be established between significant variation of shape of weld ripples and heat input rates used to make a weld of given size.

In the subsequent period equation (1) has been further examined experimentally by Milner and Apps[8] for a wide variety of metals. Their work demonstrated systematic deviations, for metals other than steel, between calculations and measurement of melted widths and welding speeds for given heat input rates. Through being largest with metals such as aluminium, having high latent heats, the source of deviation was traced. At the present time there are no accurate quantitative methods for considering latent heat as a factor influencing melted width either in cutting or welding. A uniformly applicable approximate correction is achieved by using an effective specific heat for calculation, which is the total heat for melting divided by the melting temperature, both being reckoned from ambient temperature (Fig. 2 and discussion to ref. 8).

Boundary Layer Theory of Gas and Metal Combustion

Very large combustion rates may be supported when pure iron is allowed to burn in pure oxygen. The limiting chemical combination rate does not appear to have been measured at any time, although Tucker,[9] in 1911, described how the burning time for an iron wire in oxygen of high purity could be increased eight-fold by decreasing the oxygen purity to 50%. Nusselt,[10] in 1916, showed that the reduced combustion rates with impure materials could be explained by taking into account the diffusion of the oxidizing gas through stagnant layers of its own impurities and the gaseous products of combustion near the combustion face. Nusselt's analysis was concerned with carbon, in air or oxygen. This hypothesis also applied to iron and oxygen combustion if the resistance due to the thin molten oxide layer, as well as the chemical resistance, could be ignored.

In regard to the period of activity now described, it was recognized at the outset that this hypothesis, largely confirmed hitherto from studies of fuel combustion, should closely apply to the conditions in oxygen cutting. A theory was further propounded for the special conditions arising in this case.[11]

For the steady diffusion at constant temperature of one gas through a second gas, stagnant at the interface, the rate of diffusion, N g.mol/sec, of the first through unit area of the interface has been shown by Stefan[12] to be given by equation (2) if there is no change of total pressure across the boundary layer:

$$N = \frac{DP}{RTx} \log_e \frac{p_1}{p_2} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where D = diffusion constant of the first gas through the stagnant gas, sq.cm/sec
P = total pressure, atm
R = gas constant for 1 g.mol., 82·1 c.g.s. units
T = absolute temperature, °K.
x = thickness of boundary layer separating the face from that part where the gases are in constant proportions, cm
p_1 = partial pressure of stagnant gas at interface, atm
p_2 = partial pressure of stagnant gas in body of mixed gases, atm

If there is little resistance to combustion at the interface itself, it follows that $p_1 \rightarrow P$, and the rate of diffusion becomes:

$$N = \frac{DP}{RTx} \log_e \frac{1}{\eta} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

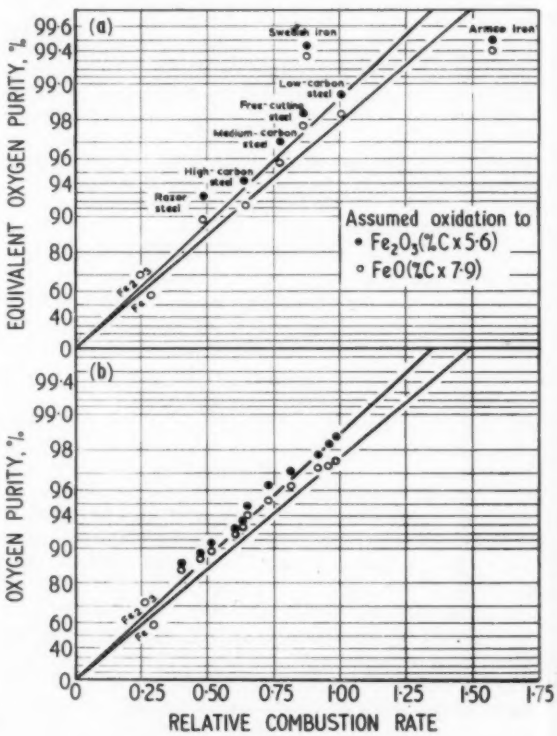
where p_2/P is the partial pressure ratio, equal to the volumetric fractional impurity η of the diffusing gas.

Experiments to Examine the Boundary-Layer Hypothesis

The boundary-layer thickness x depends on the aerodynamics of the combustion face and gas flow system, as in the analogous conditions of friction and heat transfer in fluid flow.

An experiment was required for the verification of this theory. Although it would have been appropriate to use conditions of actual cutting, it was recognized that the necessity for a pre-heat flame would make difficult the estimation at this stage of the output of heat from iron and oxygen combustion. It was argued that it would be easier to maintain combustion if the loss of heat from the combustion face by conduction could be reduced, and this led naturally to consideration of a combustion face maintained across the end of a round iron bar. It was found possible to maintain such combustion by rotating the bar so that the hot upper surface could always be presented to the impinging oxygen jet.[11] For given oxygen velocity and bar diameter the limiting condition was the speed at which the bar could be projected into the oxygen jet without stopping combustion. From the speed, the superficial combustion rate could be calculated as equal to the heat necessary to melt away unit cross-sectional area of the bar at this speed.

The first experiments were addressed to the influence of oxygen impurity. The latter could be selected by bleeding known amounts of nitrogen into oxygen of a standardized commercial purity of 99·7%. In these experiments the logarithmic influence of impurity of equation (2) was confirmed, when bars from one batch of mild steel were used (Fig. 3). However, in exploratory work, bars of different sources and compositions had been employed and marked divergences had been recorded, particularly with steels of high carbon content. This led to consideration of the influence which carbon and other elements might have in reacting with oxygen. Apparently, when gaseous compounds resulted, these would require to be removed from the boundary layer by diffusion back into



3—*Effect on combustion rate of* (a) *carbon content at standard oxygen purity (99·7%); and* (b) *oxygen purity (0·195% C steel)*

the main stream, which would be further contaminated thereby.

A hypothesis was produced to include this effect, as follows:

If the solid contains y% by weight of a contaminant, which reacts with each molecular volume of diffusing gas to replace m times the quantity of main solid and form n molecular volumes of gaseous contaminant which must diffuse back into the stream, it follows that the main stream purity at the edge of the boundary layer is reduced by an amount η_c, given by:

$$\eta_c = \frac{mny}{1+y[m(1+n)-1]} \quad \ldots\ldots\ldots\ldots (4)$$

$$(\eta \simeq mny, \text{ if } y \ll 1)$$

The value of η_c may then be added to η in equation (4) to derive the corresponding diffusion rate. The theoretical suppressing effects on combustion rate of iron and oxygen due to the contaminating elements carbon, sulphur, and phosphorus are each significant, but carbon is most important.

Experiments were performed with many iron–carbon alloys and oxygen of standard purity, which again confirmed the logarithmic effect of equivalent impurity on combustion rate (Fig. 3). In this case, however, there were two notable exceptions in Swedish and Armco irons, which showed relatively high and low combustion rates respectively. Also, although it would have been desirable to consider the well-known reluctance for combustion between oxygen and cast iron, this material could not be made to burn in the existing apparatus.

These divergences were examined over a considerable time before even a partial understanding emerged. It is now agreed that the distribution of chemical constituents within the structure of a metal has an effect on combustion. For instance, the carbon in cast iron may be partly distributed as flat flakes or as discrete spheroidized globules. Combustion is not possible with the former material but takes place at approximately the calculated rate with the latter. It is conceivable that there is an analogous microstructural influence with Swedish and Armco irons.*

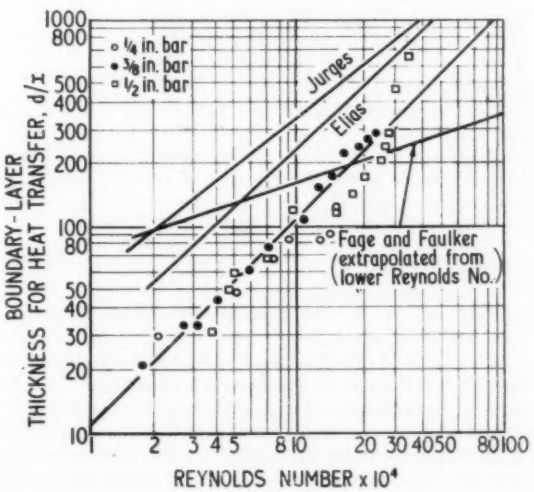
The essentially good agreement between the measured and calculated combustion rates with impurity variations for the boundary-layer hypothesis encouraged further examination of the aerodynamic influence on the boundary layer. Other things being equal, it was assumed that boundary layers would become thinner with increased oxygen pressures and velocities.

However, experiments on the round-bar combustion equipment gave disappointing results, which were eventually attributed to the complex aerodynamic conditions on the combustion face. For instance, step formations had been observed to occur as the bars rotated at the highest rates of axial traverse for given oxygen pressures. The scaling relationships were studied experimentally by varying bar diameter between $\frac{1}{4}$ in. and 1 in. Plots of combustion rate against oxygen velocity showed in each case two regimes separated by a point of instability. Although changes from laminar to turbulent flow might have been suspected, success was never achieved in correlating this behaviour. On the other hand, it was found possible to predict combustion rate with encouraging accuracy from an experiment with a heat-flow analogue (Figs. 4 and 5). In this experiment the end of a bar was heated at a controlled rate at one end so as to supply the losses through a boundary layer maintained across the opposite end by a transversely impinging air or oxygen jet.

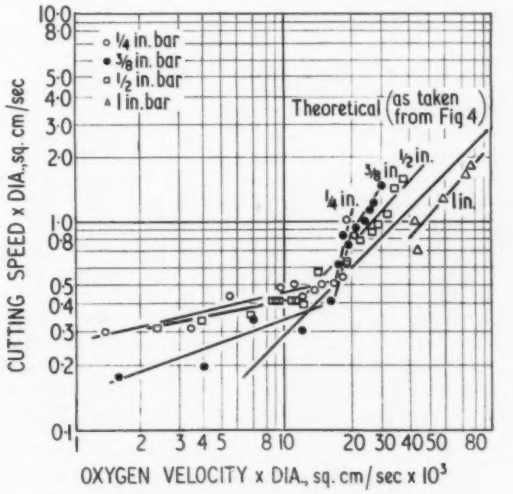
Ignition Temperature

It is customary to accept the existence of a discrete ignition temperature in some combustion studies. Although combustion rates may be primarily controlled by impurities when reaction is taking place

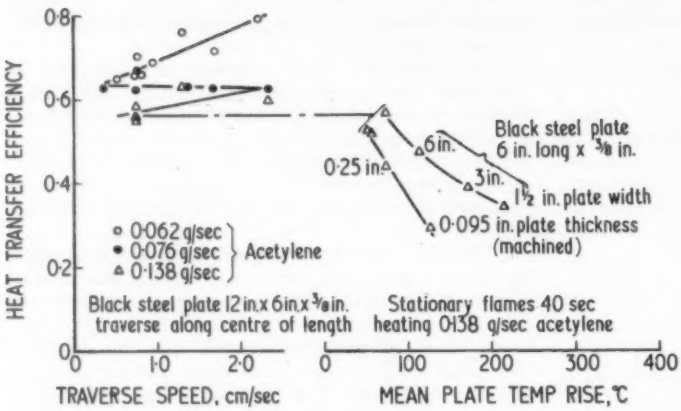
* This has been subsequently confirmed. Combustion rates are lowered by grain boundary carbide films.



4—*Boundary-layer thickness from heat-flow analogue*



5—*Comparison of measured and calculated combustion rates*



99·7% purity oxygen
Commercial dissolved acetylene
0·031 in. dia. oxygen injector orifice
Nine annular holes on 0·187 in. pitch circle
Nozzle height 0·25 in.
Oxygen-acetylene mass ratio 1·75
Oxygen pressure 30 lb/sq.in. gauge
Calorimeter corrections for water evaporation

6—Oxy-acetylene preheating flame heat transfer efficiencies (Coates[15])

between substances of commercial degrees of refinement there is still a finite reaction rate with chemically pure reactants. This limitation, of thermodynamic origin, is related to the temperature achieved in the reaction, and the latter influence may be so pronounced that the simple conception of an ignition temperature becomes possible under narrowly defined conditions.

The maintenance of an ignition temperature is obviously important in oxygen cutting, as it is obvious that combustion can normally neither be started nor maintained without a preheating flame. The distinction between gas and solid phase combustion on the one hand and combustion between gases on the other is interesting in the sense that the latter requires no separate agency for the maintenance of combustion. It is possible that stability depends upon minute amounts of re-circulation within the combustion zone, so that chilling does not arise from the entry of fresh reactant. Certainly, much consideration was given to the mechanism of reaction stability in oxygen cutting, both in the search for understanding, and with the purpose of dispensing with the preheating flame so that combustion rate studies might be extended into the field of plate cutting.

Experiments were mainly performed with plates preheated to a high temperature before an oxygen jet was applied[13,16] and with high-frequency induction heating substituted for the preheating flame. Through the successful maintenance of combustion in these experiments, particularly in the latter case with intense local heating near the cut, it was confirmed that the maintenance of an ignition temperature at the point of impingement of oxygen is the only necessary adjunct to combustion stability in that instance, and that the preheating gas flame does not necessarily fulfil any fluxing, catalyzing, or other chemical function. In spite of many attempts, no simple yet effective way of dispensing with a preheating flame in oxygen cutting was discovered, as a result of which the studies of combustion rate in plate cutting were eventually performed with the use of the smallest possible preheating flames.

Prior to quantitative work it was necessary to measure the heat-transfer efficiencies of preheating flames.

Flame Heat Transfer Efficiencies

In a flame caused by the reaction of commercially pure fuel and oxidant gases it is possible to account for most of the theoretical heat evolution; some is dissipated by gas convection and radiation; the remainder is transferred to any solid body placed near the flame. The heating may even be so intense that the surface of the solid being heated re-transfers heat to the atmosphere to leave no tangible evidence of the course of the particular component of heat into and out of the solid. It is possible by means of calorimetry to estimate that proportion of the heat evolved which is usefully absorbed into the heated body, and this fraction is defined as the heat-transfer efficiency. Before measurements could take place it was necessary to develop the calorimetry methods.[14] In particular it was discovered by Coates that significant errors could arise when, through plunging a plate with very uneven temperature distribution into the calorimeter liquid, local boiling took place. High boiling point liquids were not found to offer great advantage. By keeping other conditions constant and varying the time between the end of heating and immersion in the calorimeter it was found that the highest temperature rises occurred with intermediate times (sufficient for equalization within the body) and that a suitable correction to compensate for boiling could be made by extrapolating the temperature rise for longer delay times back to zero time. Where necessary, satisfactory corrections were established for the mass of water evaporated from the calorimeter.

Measured efficiencies for preheating flames governed by an injector orifice 0·031 in. dia., playing on steel plates $12 \times 6 \times \frac{3}{8}$ in. are shown in Fig. 6. Flame size is shown to have a significant effect. In contrast, insignificant differences were observed when the following changes were made:

(*a*) Heating times between 12 and 50 sec with stationary flames
(*b*) Nozzle plate distances between 0·1 and 1·6 in.
(*c*) Plate surface conditions between 'machined' and 'heavily rusted'.

The marked effect of altering the mean temperature rise of the plate through diminishing its size or thickness is also shown in Fig. 6. Since a correction for evaporation has already been applied, the diminished efficiencies must be attributed to reduced total heat transfer by gas convection, and in particular to re-transfer by convection from the plate at increased mean temperature.

In spite of these differences, the variations with standard oxygen cutting preheating flames were not found to be great, if confined in operation to relatively large flat plates under the conditions of normal use. Measurements with a thermopile confirmed that an insignificant proportion of the heat-transfer loss could be associated with radiation from the non-luminous flames normally used, in spite of high flame temperatures, but discrete convection loss could be detected.

Boundary-Layer Hypothesis in Plate Cutting

Although conditions differ between combustion with oxygen on the end of an iron bar, and oxygen cutting of plate, the differences would be expected to be mainly aerodynamic. It was considered that there would be a possible comparison of the boundary layers existing at the entry to a tube with high-speed axial gas flow and within the plate adjacent to the oxygen jet. Further, it has been shown in gas-flow studies that the conditions at the entry to a tube are identical with those on a flat plate placed parallel to a gas stream of infinite extent and uniform velocity[15] up to a Reynold's number ulp/μ of 3×10^5, and for subsonic or supersonic flows of moderate Mach number.

Thus:

$$x = 5{\cdot}2\, l \Big/ \sqrt{\left(\frac{ulp}{\mu}\right)} \quad \ldots\ldots\ldots\ldots \quad (5)$$

where x = boundary layer thickness, cm
l = distance from leading edge, cm
u = main stream gas velocity, cm/sec
ρ = gas density, g/sq.cm
μ = gas viscosity, dyn sec/sq.cm.

This gave the possibility of designing experiments for the correlation of combustion rate on unit surface area within the cut and the Reynold's number for the combustion face, in turn dependent on the jet velocity and the length of the gas flowpath along the cut face. In this examination combustion rate would be measurable from the cut width and speed,[7] the thermal properties of the iron, and a correction for external heat supply from the preheating flame rather than by iron and oxygen combustion. It has already been mentioned that exploratory experiments did not give the possibility either of dispensing with the preheating flame or of replacing it by another source of heat where the input would be more readily measurable. Therefore, it was decided to conduct normal plate cutting experiments with preheat flames reduced to about one third the normal intensity, so that errors in heat input estimation from this source would not seriously affect overall accuracy.

Experiments were conducted with mild steel varying between $\frac{1}{2}$ in. and 6 in. thickness and with the widest possible variations in oxygen nozzle diameter and oxygen pressure.[16] Individual cuts were made at constant pressure with step-wise increases of cutting speed until the cut was lost. The drag markings on the faces were then examined to assess the limiting combustion rate condition for the highest stable cutting speed. As would be expected, this was found to be associated with drag length.

The results permitted an encouraging correlation between cut width and speed and Reynold's number* inclusive of measured combustion rates (equation 1) and calculated values (equations 3, 4, and 5). The correlation appeared to be unique except for the smallest oxygen nozzle diameters and small plate thicknesses, where lower combustion rates than those calculated were observed. There is at present no complete understanding of these lower combustion rates but, since they were associated, as already mentioned, with the smaller absolute nozzle diameters it is plausible that the oxygen jet was contaminated by gaseous combustion products from the preheating flame to a much greater extent in these cases.

If proven, the latter result might be of considerable practical importance. The possible ratio between cut width and depth with plates above 2 in. thick is quite small. Dimensional theory suggests no reason why this ratio should not be comparably small with thinner plates, yet the experiments did not support this. If one could use smaller diameter jets for plate of 1 in. thickness and less, cutting speeds would be proportionately raised and cut faces might also be better finished. To do this it might be necessary, on the above hypothesis, to replace the gas preheating flame with another type of local heat source so as to avoid oxygen jet contamination.

Oxygen Cutting of Metals other than Iron

The evolution of a working hypothesis for oxygen cutting leads naturally to a more general consideration of solid and gas combustion for the cutting of other materials. A survey was conducted by Coates[17] with the purpose of assessing (*a*) to what extent oxygen cutting could be extended to metals other than iron, and (*b*) the cutting facility of the halogen gases and others with various metals.

Three conditions were postulated:

(i) Physical: The combination of solid and gas should preferably result in a product which is liquid at the melting temperature of the solid. Gaseous combustion products produce contamination of the impinging gas stream
(ii) Chemical: There must be an exothermic reaction, and ignition temperature below the melting temperature of solid and combustion product
(iii) Thermal: The heat generated by the reaction must be sufficient to overcome the heat of melting and the losses by conduction, convection, and radiation. This condition may be stated quantitatively in terms of heat of reaction, melting temperature, specific heat, and thermal diffusivity.

Considering first the reaction between oxygen and the metallic elements as at present known, the three satisfying the above conditions are iron, titanium, and vanadium. Experiments were performed first with titanium[18,19] and, secondly, with vanadium,[20] both of which were found to be readily cut with standard equipment. The calculations predicted a strong reaction with titanium and this was confirmed experimentally. Cutting speeds were approx. five times those for steel, other things being equal. The cutting potentiality of titanium was determined independently in this way. Brief references to commercial exploitation of oxygen cutting of titanium were also discovered.

Of the other gases likely to react with metals, chlorine was considered appropriate for the first

* See Fig. 2 of report A4/3/58, p.84 of this issue.

examination, with the metals zinc and copper, and their alloy brass.[17] Although other conditions were satisfied, the ignition could not be maintained with zinc because of its low melting point. With copper the reaction, although exothermic, did not appear to be strong enough to overcome heat losses by conduction. Limited success was achieved with brass, which has both a sufficiently high melting temperature for ignition to become possible, and a lower thermal conductivity than copper. The results did not, however, point to any possibility for exploitation, especially when considering the toxic nature of the cutting gas.

The possibility of cutting copper with fluorine has been described elsewhere. Yet another possibility, of cutting magnesium with nitrogen, was investigated without success, and it was concluded either that the nitrides which were formed were not fluid at the melting temperature, or that the melting temperature of the metal was insufficient for maintenance of the reaction.

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BOOK REVIEW

W. D. BIGGS: "*The Brittle Fracture of Steel*", London, 1960, Macdonald and Evans, 450 pp. (70*s*.)

Although one hesitates to welcome yet another addition to the voluminous literature on brittle fracture, it must be admitted that Dr. Biggs has performed a very useful work in reviewing the present state of knowledge on the subject, and by presenting in compact form a wealth of data and references.

The subject is well subdivided according to classification of fractures, service experience, mechanisms of fracture, effects of external conditions, metallurgical variables, and the discussion of mechanical tests. There are chapters on the relationship of welding and residual stress to brittle fracture. The treatment is competent, thorough and objective.

The chapters on welding and residual stress in relation to brittle fracture are probably the least conclusive, for the simple reason that this is one of the regions in which the available knowledge is most confused. However, ample data and references are given, with an adequate discussion.

The specialist and student of this complex subject will probably find more value and inspiration in the book than will the engineer faced with immediate problems of design and selection of materials, but the style, presentation and illustrations are abundently clear, so that even the layman will find it readable, and undoubtedly of considerable interest.

In reviewing a book so thoroughly documented and rich in references it may seem churlish to point out some omissions, but in view of the importance which the book attaches, particularly in the Summary, Chapter XII, to the exhaustion of ductility at the roots of notches, it would have been appropriate to refer to the work of D. C. Drucker, C. Mylonas and others on this topic. Nevertheless, the book is more generous in references than some other recent publications on the subject.

The book has few blemishes apart from some curious phraseology, as for example when it is stated on page 24 that a severe winter *caused* a major failure in a tanker, and on pages 20 and 28 there seems to be some confusion between bending moment and stress. On page 22 the word "bilge" should obviously read "bridge", and on page 394 many will be relieved to read that "a high manganese carbon ratio will not necessarily promote a *high* transition temperature".

The book correctly gives the impression that brittle fracture is a vitally important but very intractable problem which is by no means solved, and ends with the trenchant pointer:

> "The greatest need is clearly that of a deeper understanding of the fundamental mechanisms of flow and fracture—in the long run this is probably the only method by which a full solution of the problem will be achieved."

G. M. BOYD

B.W.R.A. REPORT

By F. Watkinson, B.SC. (ENG.), L.I.M.

Welding of Medium-Carbon Low-Alloy Steels

RELATIONSHIP BETWEEN WELDABILITY AND TRANSFORMATION CHARACTERISTICS

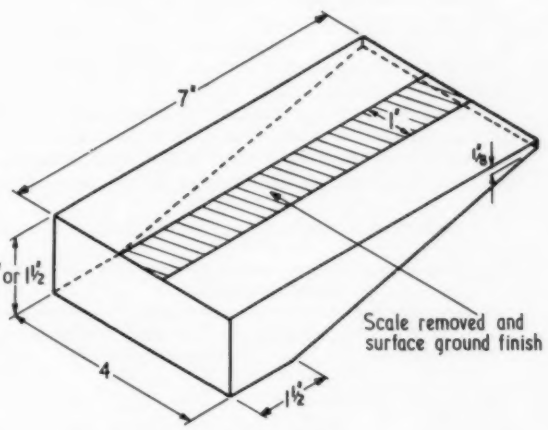
The paper concerns the development of methods of testing medium-carbon low-alloy steels to ascertain the relationship between weldability and transformation characteristics in a number of steels. The work covered two distinct but related aspects: (a) *an attempt to establish a relationship between hydrogen content and critical cooling rate, for cracking; and* (b) *the determination of the continuous cooling transformation temperatures of the steels investigated for the further purpose of correlation with the critical cooling rate.*

RECENT work by B.W.R.A. has been focused on the establishment, for a wider range of steels than previously considered, of the relationship between transformation characteristics and the tendency to heat-affected zone cracking. Previous work[1] on a limited range of steels has shown that, for a given hydrogen level, there is a critical end-of-transformation temperature, and continuance of transformation below this corresponds to the onset of cracking in the heat-affected zone. Steels of higher carbon content and different combinations of alloying elements have been used. The work may be considered in two main parts. The first deals with the attempt to establish the relationship between hydrogen content and critical cooling rate (for cracking) for the series of steels considered. The second part comprises the determination of the continuous cooling transformation temperatures of these steels and the attempt to relate critical cooling conditions with transformation temperature.

The first part of the programme has involved the development of a cracking test, different in geometry from that of the C.T.S. test, which provides the necessary range of cooling conditions in a single test. Suitable methods of depositing weld metal containing controlled amounts of hydrogen have also been developed. The B.W.R.A. high speed dilatometer has been used to determine the transformation characteristics of the steels investigated, over the range of cooling conditions experienced in arc welding.

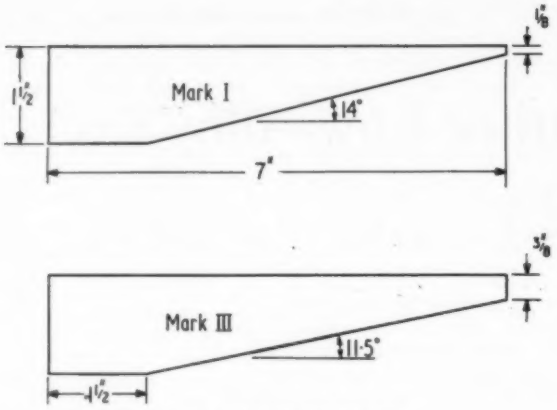
Development of the Wedge Test

In an attempt to economize on material and manpower, a test was sought which was easy to prepare and examine, and which at the same time provided a range of cooling conditions similar to those found in a set of C.T.S. test assemblies. The test, selected and subsequently developed as a cracking test, was a wedge test originally used for the microstructural study of transformation behaviour in mild steel under arc welding conditions.[2] The test wedge was modified in shape, and the welding conditions were so adjusted as to give a suitable range of cooling conditions in the heat-affected zone of the weld. Figure 1 shows the dimensions of the first two wedge shapes tested. These were prepared from 1½ in. and 1 in. thick plates. The welding conditions chosen were those used in the standard C.T.S. test. Using 8 s.w.g. electrodes and the normal deposition current, welds were made at the rate of 1½ in. of electrode per inch of weld deposited. From these tests typical cooling curves from different positions along the wedge were obtained. The thermal cycles experienced over the length of the test wedge were equivalent to those experienced in the C.T.S. tests of thermal severity numbers ranging from 10 to 4. Figure 2 shows the dimensions of the modified wedge shape test block (Mark III) which was finally adopted as giving the best range of cooling conditions, and Fig. 3 shows the cooling curves obtained along this



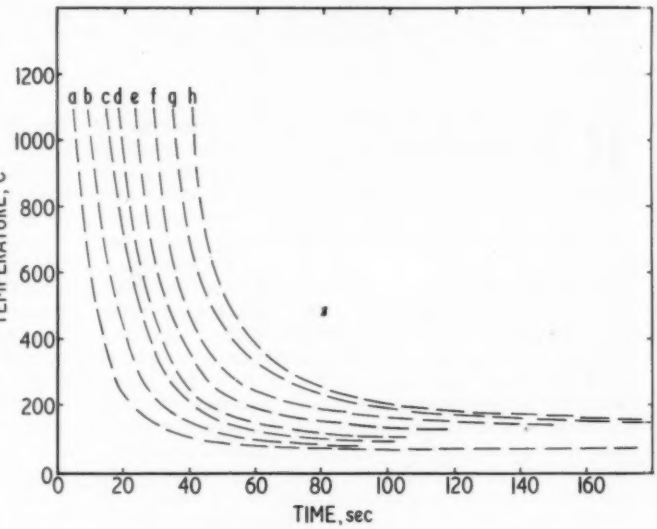
1—*Dimensions of the two wedges used*

Report B2/10/60 of the British Welding Research Association, circulated to members in May 1960.
Mr. Watkinson is a Research Officer with the Association.

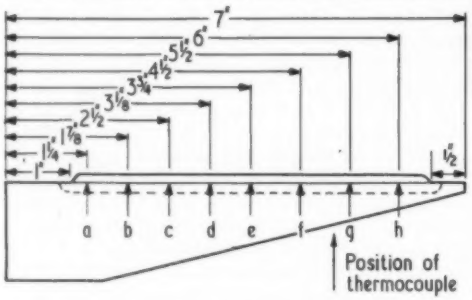


2—*Taper sections of Mark I and Mark III wedges*

3—*Cooling curves for Mark III wedge welded automatically*



4—*Positions of thermocouples in heat-affected zone*



wedge at positions defined in Fig. 4. Table I lists the cooling rates at 300°C. obtained from these cooling curves.

Actual cracking tests were made on wedge blocks of both thicknesses. The steel used was developed by B.W.R.A. (*AB*); its composition is given in Table II. The electrodes used were rutile coated class E3—(B.W.R.A. Serial No. 68).

The method of examination in these tests was to section the test weld longitudinally on its centre line, to reveal the heat-affected zone. After local electrolytic polishing and etching the section was examined for cracking and the position along the wedge at which the last crack was observed was then related to the cooling rate at that position. A comparison is given in Table III between the critical cooling rates of this steel in different tests, including the C.T.S. test and a wedge test using a smaller gauge electrode.

The thermal reproducibility of the established wedge test has been checked over a number of different tests, and Table IV shows the variation, over eight tests, of the cooling rate at a fixed point in the wedge geometry.

Control of Hydrogen in Weld Metal

There is evidence of a distinct relationship between the hydrogen content of a weld metal and its tendency to produce heat-affected zone cracking in certain low-alloy steel base plates.[3] The complete establishment of such a relationship has been hindered by the inability to deposit weld metal of any desired hydrogen content over the range from 2 ml to 30 ml per 100 g of deposited metal. Attempts have been made therefore to fill the gaps in this range which are not covered by normal welding electrodes.

Table I

Heat-affected zone cooling rates for the Mark III wedge shape welded automatically

Test Condition	*Cooling Rate at 300°C. (°C/S) at Thermocouple Position*							
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*
Mark III (11·5°) wedge Energy input rate 34kJ/in.	28·3	21·2	18	17·7	13·2	7·9	6·1	6·2

Table II

Analysis of B.W.R.A. Steel AB

C, %	*Si, %*	*Mn, %*	*S, %*	*P, %*	*Ni, %*	*Cr, %*	*Mo, %*
0·13	0·28	0·85	0·013	0·011	1·00	0·92	0·40

Table III

Comparison of critical cooling rates under wedge and standard C.T.S. test condition

	Standard C.T.S. Test	*1½ in. Wedge+ 8 s.w.g.*	*1 in. Wedge+ 8 s.w.g.*	*1 in. Wedge+ 10 s.w.g.*
Critical Cooling Rate, °C./sec	4·53	12·3	14·5	23·6

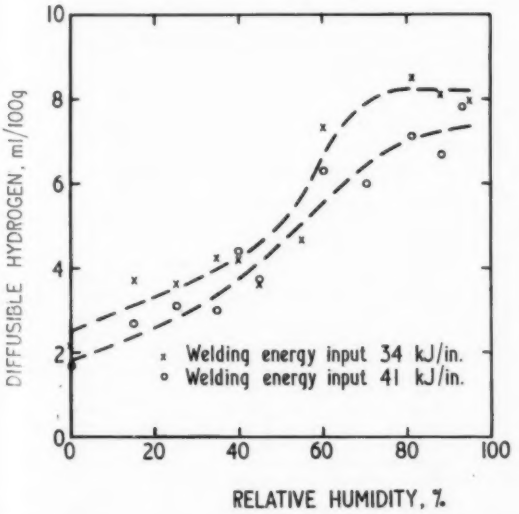
Table IV

Variability of cooling rate in the wedge test at a point 2·3 in. from the thick end

Test No.	*50*	*52*	*54*	*56*	*58*	*60*	*62*	*64*	*66*	*68*
Cooling Rate at 300°C., °C./sec	*	20·3	19·7	21·4	20·3	22·8	20·6	15·4†	19·6	21·4

* Record useless due to recorder fault † Transformation kink on cooling curve at 300°C.

The argon gas shielded consumable electrode welding process has been investigated with a view to providing a continuously variable range of hydrogen in weld metal. Using an argon-shielded mild steel wire electrode, additions of hydrogen gas have been made to the argon. In all cases investigated this led to unstable arc conditions, which in many cases resulted in severe porosity due to turbulent conditions in the shielding gas. Water vapour has also been added to argon shielding gas, by bubbling the gas through a water container, to a relative humidity of 95%. Weld metal deposited by this method has been sound and has contained up to 8 ml hydrogen per 100 g deposited metal. The lower limit obtainable by this method is 2 ml per 100 g and the relationship between the relative humidity and hydrogen content of the weld metal is shown in Fig. 5. The possibility of obtaining higher hydrogen contents by bubbling the argon through liquids of higher potential hydrogen content has been investigated. Samples of weld metal were deposited under argon shielding gas saturated in acetic acid and ethyl alcohol in turn. Table V shows the hydrogen contents obtained under these conditions. Sampling of flux-covered electrodes has shown that hydrogen levels from 2 to 10 ml per 100 g can be obtained from a typical class E6–electrode (B.W.R.A. Serial No. 122) and from 20 to 30 ml per 100 g from a typical class E3–electrode (B.W.R.A. Serial No. 68) according to the drying treatment given to these electrodes. Special class E3–electrodes of the same manufacture as above have been prepared with less than the normal amount of flux coating on the same gauge wire. Sampling of these electrodes has shown a weld metal hydrogen content of as low as 13 ml per 100 g after drying at a suitable temperature. Tables VI and VII detail the diffusible hydrogen contents obtained from these various electrodes under different conditions.



5—*Diffusible hydrogen content as function of relative humidity*

Continuous Cooling Transformation Characteristics

The C.C.T. characteristics of the steels used in this work have been determined by means of the B.W.R.A. rapid response dilatometer. In this instrument, changes in length of a hollow cylindrical specimen, which are related to transformation, are converted to an electrical signal which is fed into an X–Y function plotter. The other function plotted is temperature and this is supplied by a thermocouple with wires flash-welded to the inside of the specimen. A record is thus obtained of dilatation *versus* temperature. The hollow cylindrical specimen is subjected to a simulated weld thermal cycle. The rapid heating necessary is provided by a high-frequency induction unit, and cooling from the peak temperature is controlled by passing over the specimen a predetermined volume of argon gas stored for the purpose in tanks at a definite initial pressure. The cooling cycle can be altered by using different volumes of gas or different initial pressures, and by the use of metering jets in the pipeline between the storage tanks and the specimen. A record of this thermal cycle is made on the same chart as the dilatation/

Table V

Hydrogen contents from argon saturated with organic vapours

Shield	*Sample No.*	*Diffusible Hydrogen*	*Shield*	*Sample No.*	*Diffusible Hydrogen*
Argon + Acetic Acid	H49/1	9·5	Argon + Ethyl Alcohol	H50/1	9·8
	H49/2	8·6		H50/2	9·8
	H49/3	8·3			

Table VI

Effect of drying treatment on the hydrogen contents from E3–Electrode (No. 68)

Sample No.	*Drying Conditions*		*Diffusible Hydrogen, ml/100 g*
	Temperature, °C.	*Time, hr*	
H51/1	150	1	29·6
H51/2	200	1	36·8
H51/3	500	1	18·8
H51/4	200	8	28·2
H51/5	500	6	21·7
H51/6	500	24	18·9

Table VII

Weld metal hydrogen contents using covered electrodes

Electrode	*Treatment*	*Sample No.*	*Diffusible Hydrogen, ml/100 g*
E3—Serial No. 68 Normal Coating Weight	Dried at 500°C. for 2 hr	H54/1	27·6
		H54/2	19·4
		H57/1	21·7
		H57/2	20·8
		H57/3	19·6
		H57/4	22·1
		H57/5	21·1
E3—Serial No. 68(50) 50% Normal Coating Weight	Dried at 500°C. for 2 hr	H54/5	15·7
		H54/6	13·5
		H59/1	14·0
		H59/2	12·7
		H59/3	11·6
		H59/4	12·9
		H59/5	15·0
		H59/6	14·4
E6—Serial No. 122	Dried at 150°C. for 30–35 min	H52/1	12·0
		H52/2	12·5
		H60/1	10·0
		H60/2	9·3
		H60/3	9·3
		H60/4	9·2
		H60/5	7·8
		H60/6	8·7

temperature record by means of a pen driven at constant speed at right angles to the temperature function.

The transformation diagrams obtained from these tests are shown in Figs. 6–15. Two diagrams are presented for each steel, the difference being in the time function employed. Table VIII summarizes the ranges of temperature over which martensite* is formed and compares these with the values for M_s calculated from Steven and Haynes.

$$M_s = 561° - (474 \times \%C + 33 \times \%Mn + 17 \times \%Ni + 17 \times \%Cr + 21 \times \%Mo)°C.$$

Summary of Experimental Work (Wedge Testing)

The steels obtained for investigation with a view to relating heat-affected zone cracking tendency to transformation temperatures were generally of higher

Table VIII

Comparison of calculated M_s and experimental data on martensite formation

Steel No.	M_s *Calculated, °C.*	M_s	M_{50} *Experimental, °C.*	M_f
8776	394	380–330	320–300	190–260
8D	324	285–310	245–265	70–160
15	344	310–330	265–280	120–200
43A	270	260–285	215–230	20–75
12B	302	270–320	235–255	20–110
18A	365	320–360	270–320	140–180
16(W)	334	310–335	255–295	110–190
20B	339	310–350	275–310	145–200
29B	361	330–370	300–320	165–185
27	301	270–310	230–255	65–70

carbon content than hitherto considered. These steels, which are listed together with their analyses in Table IX, were obtained in lengths of section 4 in. wide by 1½ in. thick.

The wedge blocks were cut to shape by sawing. Tests were made on these steels, using the inert-gas shielded metal-arc welding process to provide weld metal containing 8 ml of hydrogen per 100 g deposited metal. Subsequent tests were made using class E3–flux-covered electrodes (B.W.R.A. Serial Nos. 68 and 68(50)) which provided 20 ml and 13 ml of hydrogen per 100 g deposited metal respectively. The electrodes were deposited manually at the standard rate at a fixed travel speed. One insert thermocouple was usually included to provide additional thermal information, which is plotted in Fig. 16 as the time to cool from 870° to 300°C. against position on the wedge as defined by the thickness. This provides the necessary link between the critical cracking position (as determined by microscopic examination of the wedge test section), and the transformation temperatures relevant to this position.

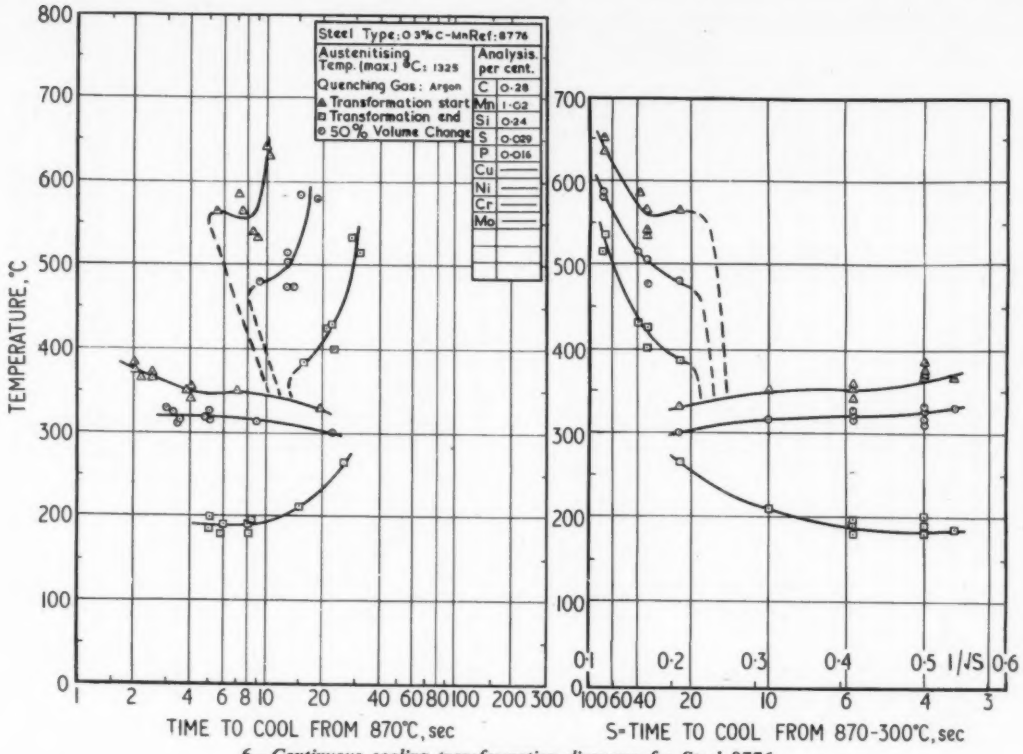
In all of the wedge tests made using only 8 ml of hydrogen per 100 g cracking failed to occur. In those made with 20 ml and 13 ml cracking did occur and a

* Judged by horizontal portion on continuous cooling transformation diagram.

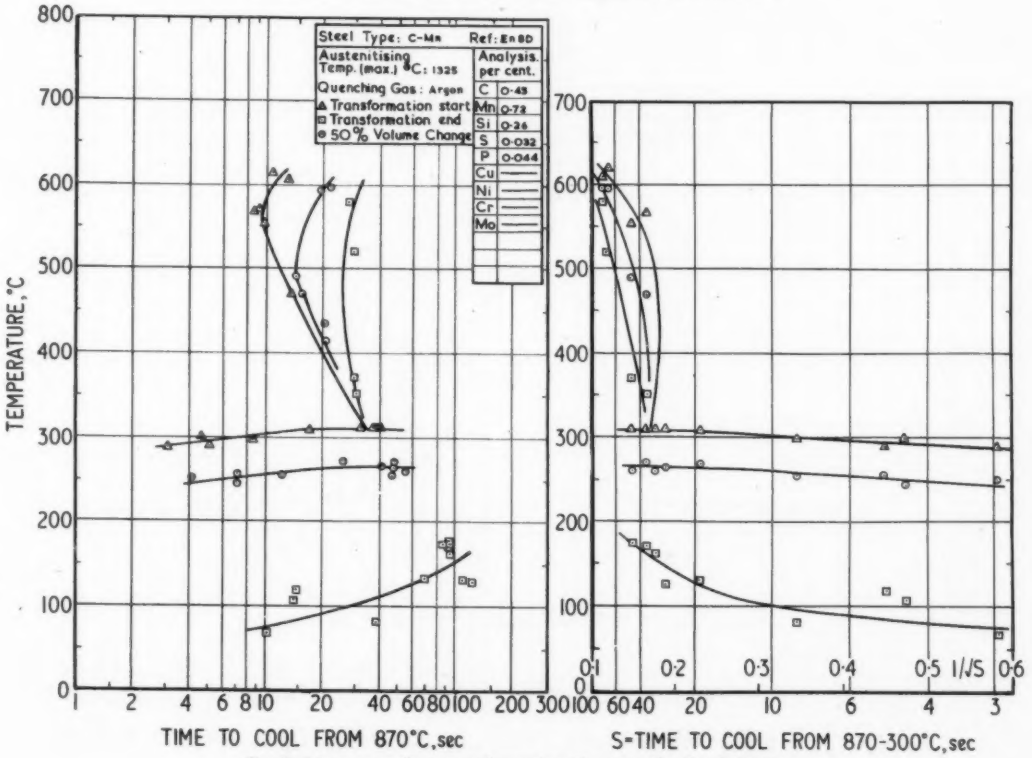
Table IX

Comparisons for effects of various elements

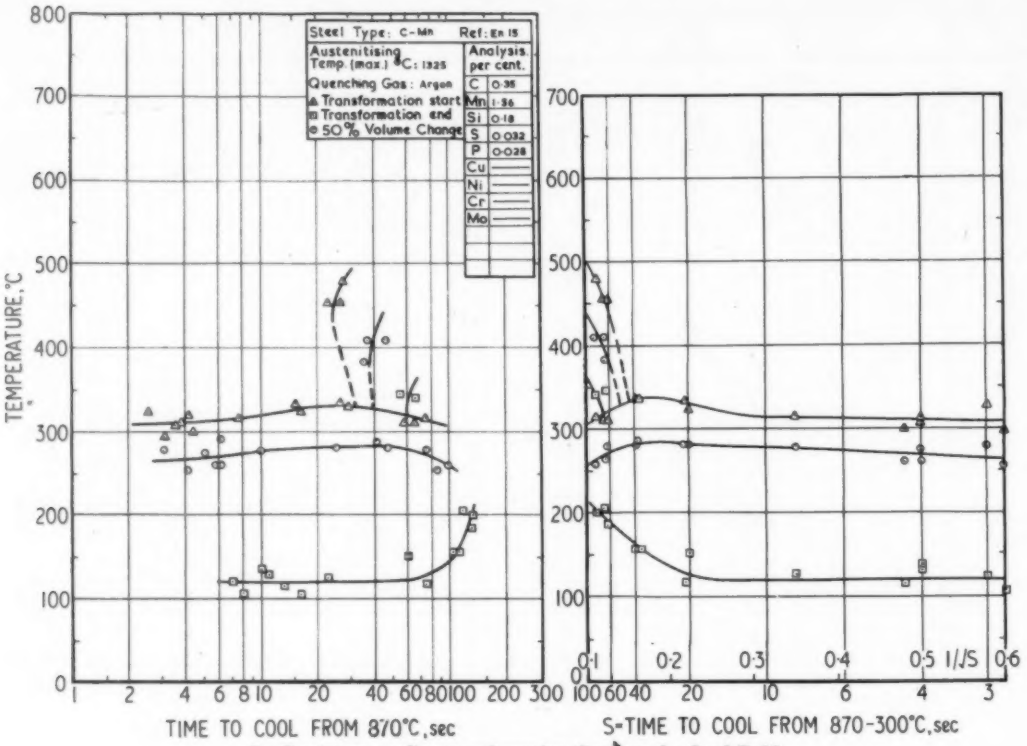
Comparison	*Steel No.*	*Cast No.*	*Composition, %* *C*	*Si*	*Mn*	*Ni*	*Cr*	*Mo*	*S*	*P*
Effect of C	8776	24/3904	0·28	0·241	1·02	—	—	—	0·029	0·016
	8D	BX103	0·45	0·26	0·72	—	—	—	0·032	0·044
	43A	Z966	0·55	0·17	0·92	—	—	—	0·033	0·030
Effect of Mn	8776	24/3904	0·28	0·241	1·02	—	—	—	0·029	0·016
	8D	BX103	0·45	0·26	0·72	—	—	—	0·032	0·044
	15	Z1036	0·35	0·18	1·56	—	—	—	0·032	0·028
Effect of Mo	15	Z1036	0·35	0·18	1·56	—	—	—	0·032	0·028
	16(W)	V4031	0·37	0·17	1·40	—	—	0·29	0·030	0·028
	16(X)	K6922	0·39	0·18	1·60	—	—	0·27	0·028	0·024
Effect of Cr (Deduce effect of Mo from above)	8776	24/3904	0·28	0·241	1·02	—	—	—	0·029	0·016
	18A	Z1037	0·32	0·19	0·83	—	0·97	—	0·029	0·035
	29B	S3861	0·27	0·29	0·50	0·13	3·10	0·25	0·014	0·031
	20B	K7275	0·36	0·31	0·53	0·14	1·21	0·57	0·020	0·030
Effect of Ni (Make allowance for Mn, Cr, Mo)	8D	BX103	0·45	0·26	0·72	—	—	—	0·032	0·044
	12B	A1928	0·44	0·20	0·86	0·91	0·35	—	0·017	0·017
	8776	24/3904	0·28	0·241	1·02	—	—	—	0·029	0·016
	27	W5017	0·34	0·29	0·66	3·23	0·88	0·34	0·043	0·030



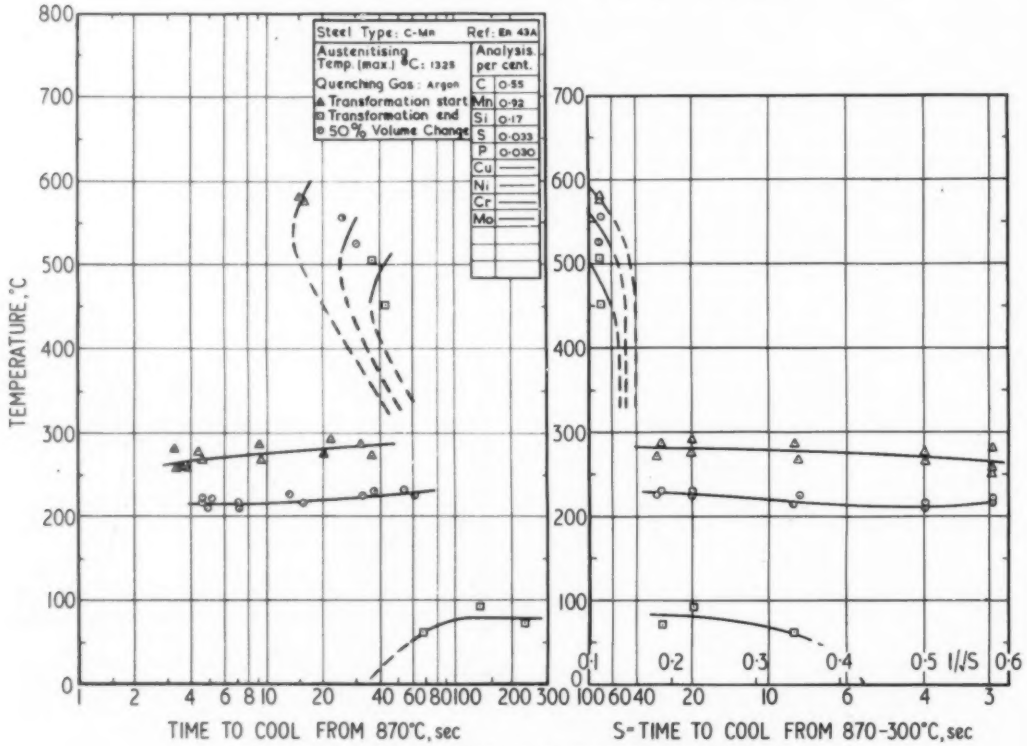
6—*Continuous cooling transformation diagrams for Steel 8776*



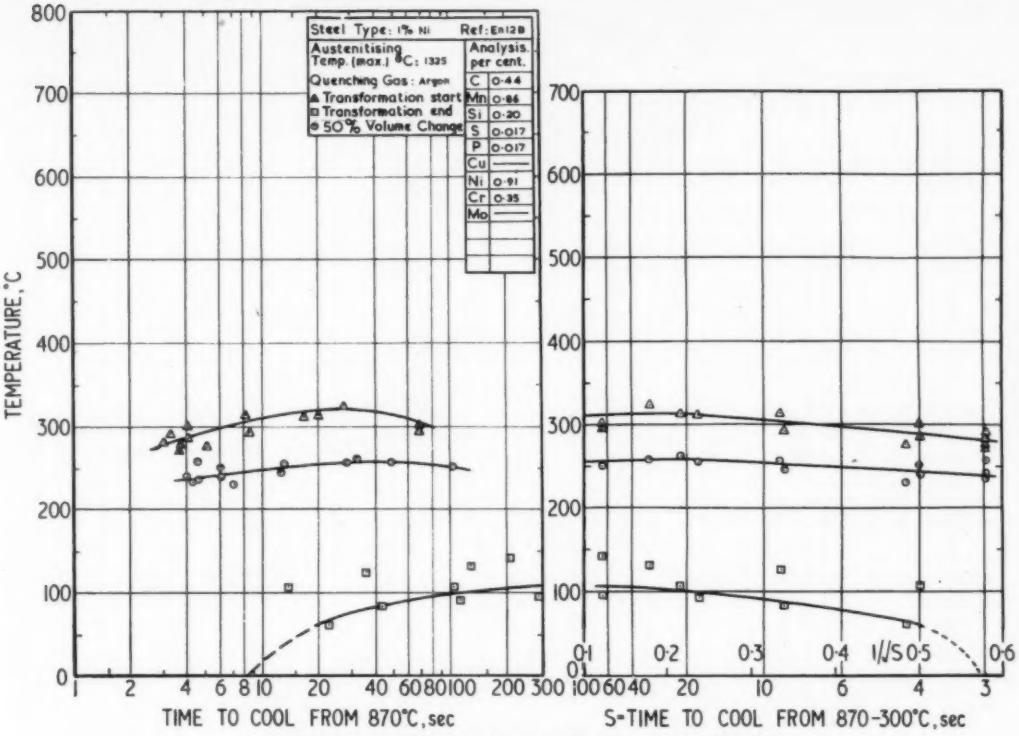
7—*Continuous cooling transformation diagrams for Steel En8D*



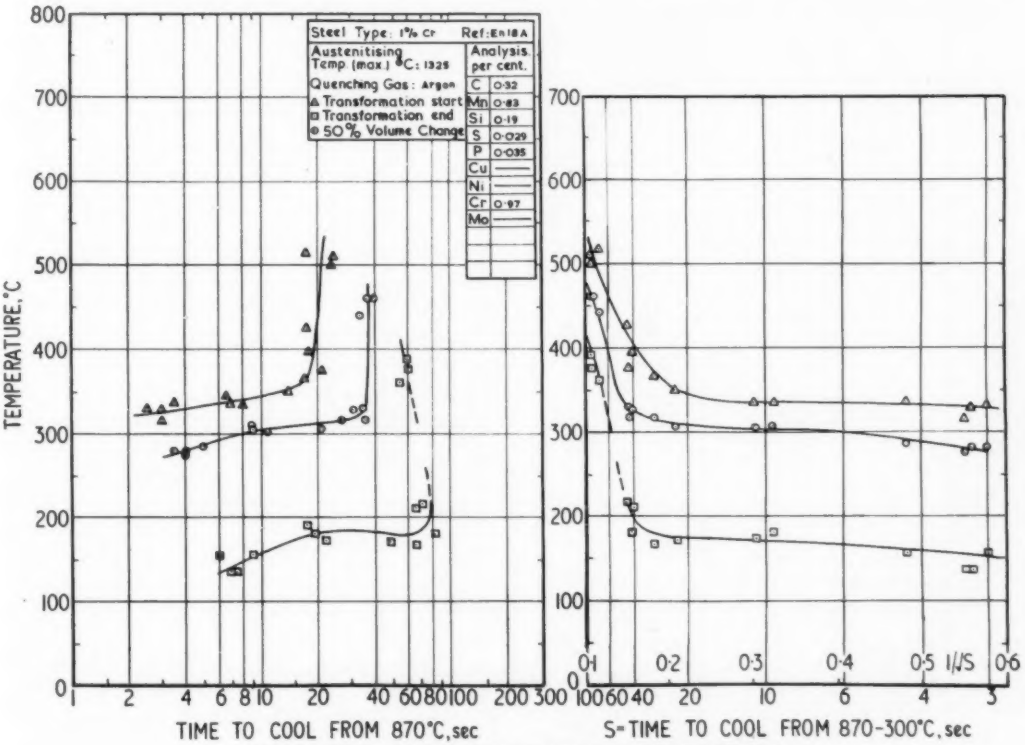
8—*Continuous cooling transformation diagrams for Steel En15*



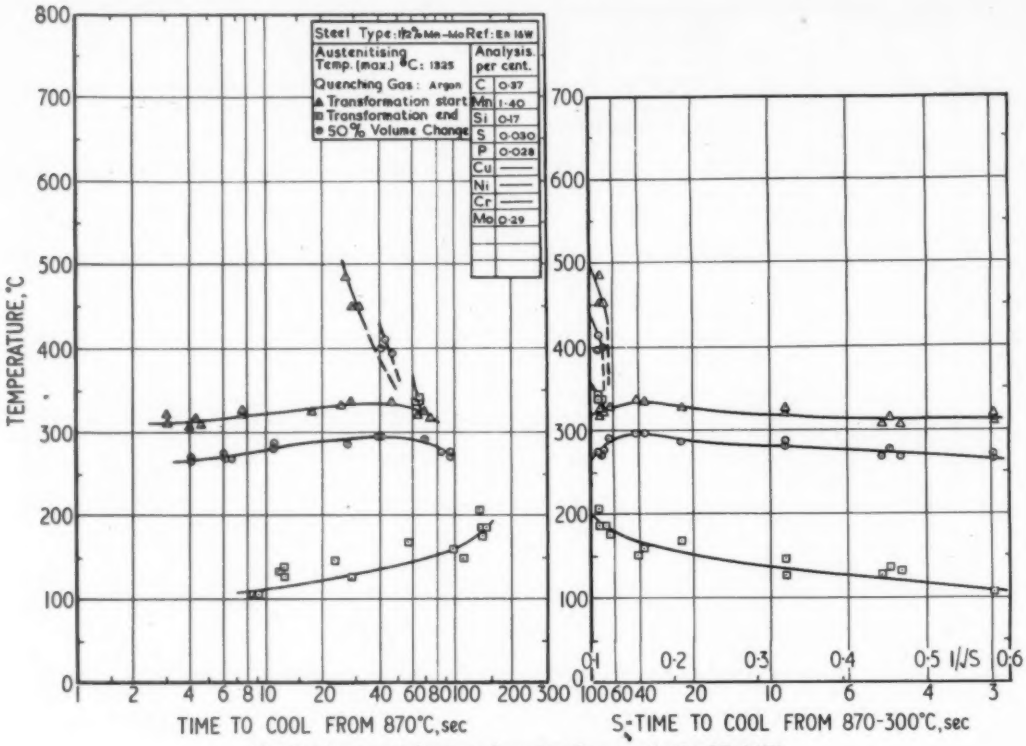
9—*Continuous cooling transformation diagrams for Steel En43A*



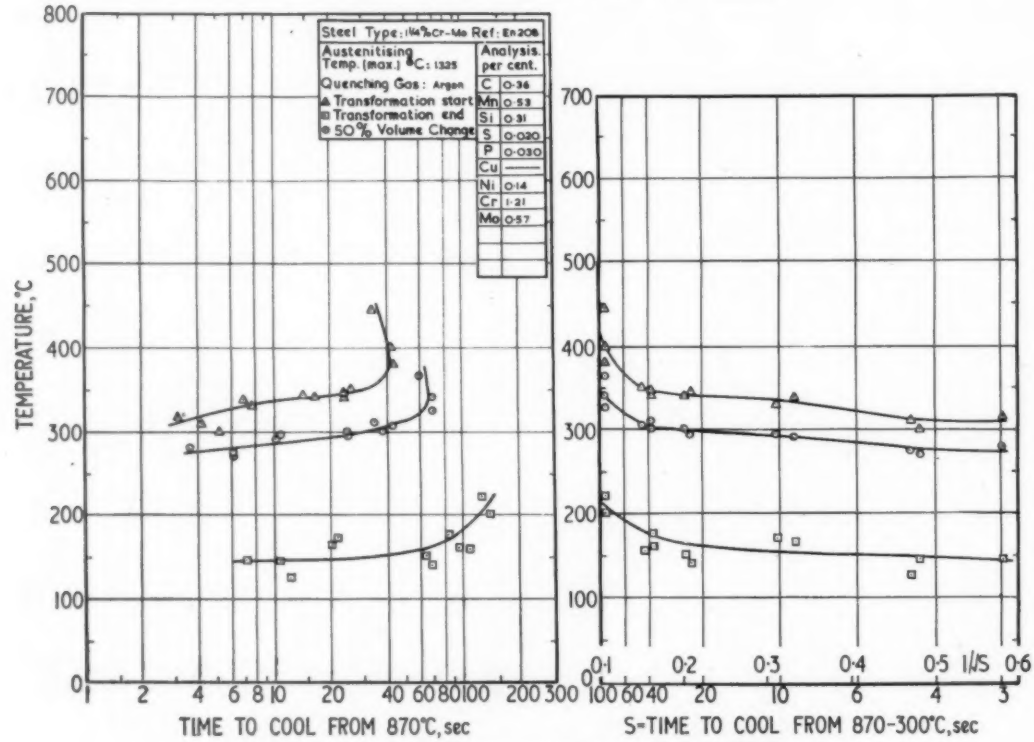
10—*Continuous cooling transformation diagrams for Steel En12B*



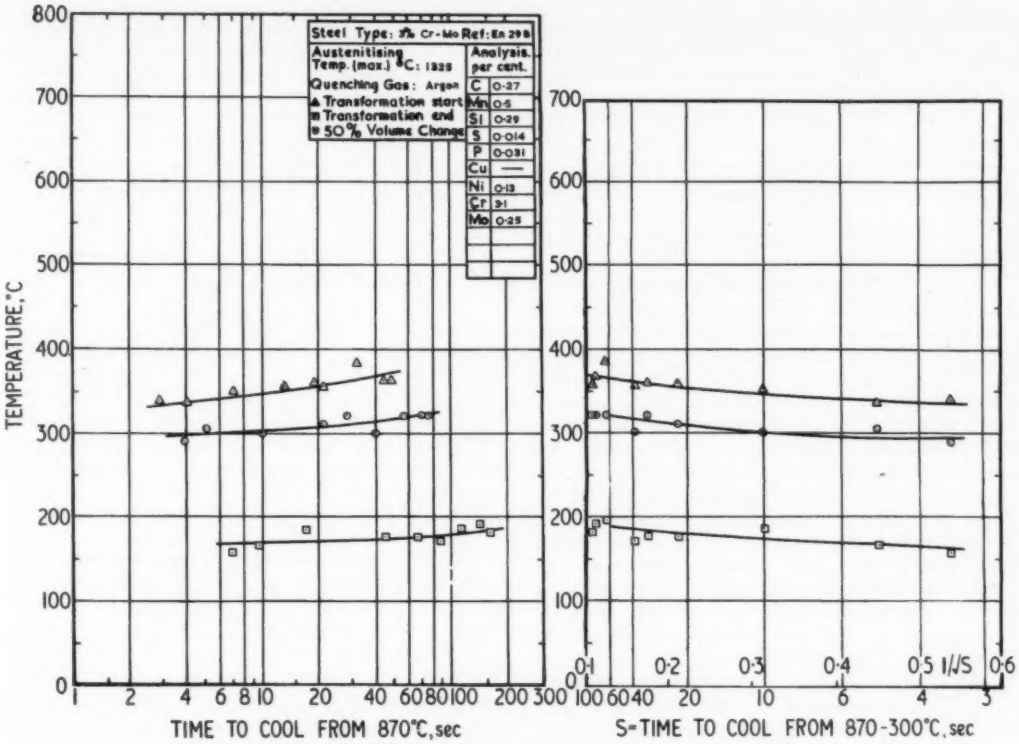
11—*Continuous cooling transformation diagrams for Steel En18A*



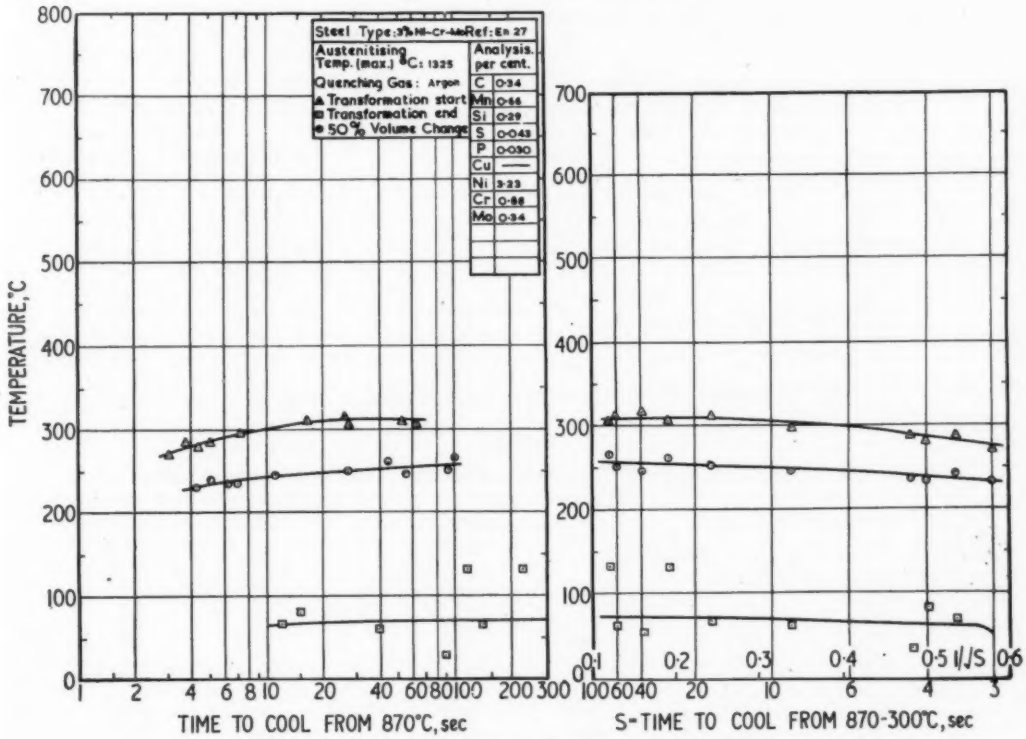
12—*Continuous cooling transformation diagrams for Steel En16W*



13—*Continuous cooling transformation diagrams for Steel En20B*



14—Continuous cooling transformation diagrams for Steel En29B



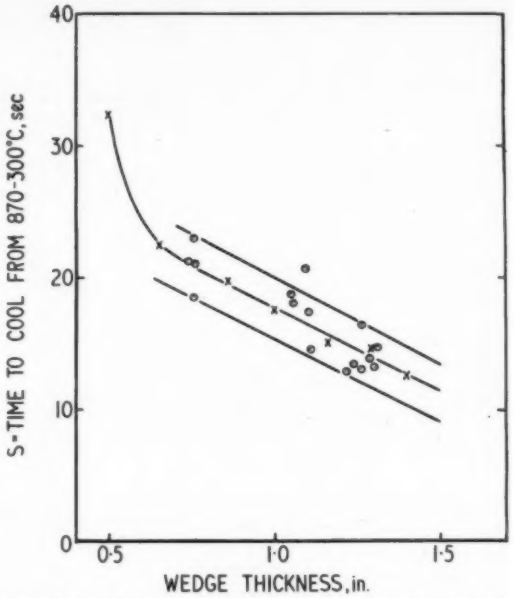
15—Continuous cooling transformation diagrams for Steel En27

summary of the information obtained from these tests is provided in Tables X and XI respectively. The tables give the critical cracking data for the steels and compare these with the transformation temperatures corresponding to the finish of heat-affected zone cracking.

Discussion of Results

From a consideration of the wedge test results obtained during the development of the wedge as a cracking test, it was soon apparent that the geometry of the weld bead and its associated heat-affected zone was important in determining the critical cooling conditions for cracking. As can be seen from Table III, differences in the geometry of the wedge block itself make little difference to the critical cooling results. However, a change in weld bead size affects the result, the indication being that with smaller beads the critical cooling rate is raised. The difference between bead-on-wedge and fillet welding conditions as experienced in the C.T.S. test is clearly indicated, the fillet type of weld being more severe and resulting in a lower critical cooling rate. The difference between these two tests shows that the wedge test cannot be substituted for the C.T.S. test, but can be used for a comparative determination of critical cooling conditions for a series of steels.

The attempt to obtain a continuously variable range of hydrogen contents from the argon gas-shielded welding process was successful, but did not cover as large a range as was hoped. The use of organic liquid vapours has extended the range only slightly. The gap in the range between weld metals deposited under gas shields and weld metals deposited from normal class E3–electrodes has been almost filled by suitable drying treatment of special class E3–electrodes, the minimum level achieved by this method so far being 13 ml per 100 g.



16—*Relationship between cooling curve parameter* S *and position on the wedge, showing extent of scatter*

Table X

Correlation of critical cracking with transformation data (nominal hydrogen level=20 ml/100 g)

Steel No. En	*Weld Metal Cracking* *Start*	*Finish*	*H.A.Z. Cracking* *Start*	*Finish*	*C.C.T. Temperatures for Finish of H.A.Z. Cracking, °C.* *Start*	*50%*	*Finish*
	Time to cool from 870°C. to 300°C., sec						
8D	nil	nil	13·0	20·3	307	265	127
15	nil	nil	13·8	20·4	330	282	126
43A	11·4	13·4	11·8	21·8	282	227	81
12B	12·4	19·7	12·7	23·4	312	258	100
18A	nil	nil	16·5	19·4	343	307	174
16(W)	nil	nil	15·0	20·3	325	286	156
20B	13·3	15·5	14·8	26·0	342	298	165
29B	13·5	17·8	14·3	22·7	354	310	180
27	9·8	13·2	13·2	19·1	308	252	70

Table XI

Correlation of critical cracking with transformation data (nominal hydrogen level=13 ml/100 g)

Steel No. En	*Weld Metal Cracking* *Start*	*Finish*	*H.A.Z. Cracking* *Start*	*Finish*	*C.C.T. Temperatures for Finish of H.A.Z. Cracking, °C.* *Start*	*50%*	*Finish*
	Time to cool from 870°C. to 300°C., sec						
8D	13·7	13·7	nil	nil	—	—	—
15	nil	nil	15·8	18·2	327	280	122
43A	nil	nil	13·3	19·4	281	226	80
12B	15·3	16·2	18·3	20·7	312	258	100
18A	nil	nil	nil	nil	—	—	—
16(W)	nil	nil	14·6	17·5	324	285	148
20B	13·2	14·9	nil	nil	—	—	—
29B	14·8	14·8	21·8	21·8	353	308	180
27	14·3	18·2	20·1	20·1	308	252	70

The rapid response dilatometer equipment has supplied reproducible information from which continuous cooling transformation diagrams have been constructed for the steels used and it will be seen that most of the steels chosen transform in fact almost entirely to martensite over the major part of the cooling range covered by the diagrams. Indeed, over the range of cooling conditions found in the wedge test, according to the transformation diagrams, all but one of the steels transform to martensite. This feature distinguishes these steels from those used in previous work where the transformation temperatures varied with cooling rate.

Table VIII shows good agreement between the calculated value of M_s and its value determined dilatometrically.

Tables X and XI, which contain the results of the wedge tests on the selected steels, provide the data for a comparison of cracking severity with transformation temperatures. The severity of cracking is indicated by the position along the wedge at which heat-affected zone cracking ends. It can be seen that there is little correlation between the severity of cracking and any of the transformation criteria listed; i.e., start, 50%, or finish. These results might be criticized on the grounds that weld-metal cracking has also taken place which could upset the heat-affected zone cracking result by causing a re-distribution of stress and/or hydrogen content. More careful examination of these tables shows, however, that in no case does weld metal cracking occur close to the finish of heat-affected zone cracking and hence little if any effect on heat-affected zone cracking can be attributed to weld metal cracking. In Table XI the result for steel En8D shows the presence of weld metal cracking but no heat-affected zone cracking. In this case the absence of heat-affected zone cracking can hardly be attributed to weld metal cracking since the latter was a single fissure.

Failure to demonstrate the relationship between cracking severity and transformation temperature for this range of steels does not in any way affect the value of the relationship established for the limited range of lower-carbon Mn–Ni–Cr–Mo steels considered in earlier work.[1] The results indicate a tendency to more severe cracking in those steels with lower transformation temperatures, but the lack of direct correlation suggests that the transformation temperature, as such, is of secondary importance where the transformation product is martensite. In lower-carbon steels the transformation temperature is of importance because this factor is more or less directly indicative of the type of transformation product. Transformation studies on these earlier low-carbon steels show that the transformation products are a mixture of intermediate transformation products, such as bainite, with martensite. Thus the transformation temperature determines the proportion of these two constituents and it seems reasonable that, the greater the proportion of martensite in the structure, the higher will be the stresses due to transformation, with an associated increase in tendency to cracking.

Future Work

The lack of success in obtaining correlation between transformation temperatures and cracking results leads naturally to a careful consideration of the microstructures associated with cracking in different steels. In particular the differences between low and medium carbon steels of different alloy contents require consideration. Apart from a study of those structures which are expected to show differences in, for instance, the type of intermediate transformation product, it is also desirable to consider those structures hitherto thought to be the same, in which recent evidence has shown startling differences when examined with sufficiently high resolution techniques.[4]

A more fundamental investigation of the effects of different alloying elements on the transformation characteristics of steels is planned. A programme involving the study of vacuum melted steel-like iron alloys, using the B.W.R.A. rapid response dilatometer will consider the effect on transformation temperatures, volume changes, and microstructures of additions of carbon, silicon, manganese, nickel, and chromium to iron.

While the results of wedge tests on the steels in this report are accepted, it is proposed also to apply the C.T.S. test. This is to be carried out to establish that the only significant difference between the two tests is one of severity, in which case the results obtained should be of the same order but achieved at a lower hydrogen level. Included in this part of the future programme will be some special high-silicon steels developed by Kenneford[5] which have low transformation volume changes and consequently low transformation stresses.

An outstanding problem in this work is the mode of initiation and propagation of cracking. Some very interesting work in this connection has just been reported by Hewitt of the United Steel Companies Ltd.[6] in which it is suggested that the effect of hydrogen on the initiation and propagation of cracking is markedly dependent on temperature. This work is to be followed up by consideration of the effects of alloy content on this mode of initiation.

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6. J. Hewitt: "The study of hydrogen in low alloy steel by internal friction techniques". United Steel Companies Ltd., Confidential Report.

NEWS and Announcements

News of the Institute and Branches
B.W.R.A. · Other Societies ·
and Industry

INSTITUTE ACTIVITIES

MEETINGS

Spring Meeting 1961

The Spring Meeting of 1961 will open, *not as announced* on Monday 24th April, but on the following day, Tuesday, 25th April 1961, when Dr. N. P. Inglis will deliver the Annual Lecture at the Institute at 6.30 for 7 p.m. His subject will be "*Welding in the Non-Ferrous Metals Field*".

The lecture will be followed by a reception ending at 9 p.m.

On the three following mornings there will be discussion meetings at the Institute beginning at 9.30 a.m.

On the Wednesday afternoon there will be a visit to the all-welded Maidenhead Bridge, and on the Thursday the Joint London Branches Dinner will be held at Quaglino's Restaurant.

Friday 28th April is the day for the official visit for members of the Institute to the Engineering, Marine, Welding, and Nuclear Energy Exhibition.

Utrecht

Members of the Institute are invited to apply to the Secretary for the programme and enrolment form for the Joint Meeting with the Netherlands Welding Society at Utrecht from 31st May to 2nd June 1961.

The programme will include the presentation and discussion of a number of papers on design and construction in aluminium, a visit to the welding exhibition organized by the Netherlands Institute and a choice of works visits, as well as a number of social engagements.

The final date for receipt of enrolments is 15th April and members are asked to accept this as the only notification.

Welding in Shipbuilding

The Autumn Meeting of the Institute this year is taking the form of a Joint Symposium on Welding in Shipbuilding, sponsored by the Royal Institution of Naval Architects, the Institute of Marine Engineers, the Institution of Engineers and Shipbuilders in Scotland, and the North East Coast Institution of Engineers and Shipbuilders.

More than thirty papers dealing with problems of design, construction, and quality control have already been promised and include contributions from Denmark, France, Italy, Japan, the Netherlands, Poland, Sweden, and U.S.A. It is already clear that the programme will involve eight technical sessions spread over four days, and effectively that with social engagements it will fill the week 30th October to 3rd November 1961.

All papers will be preprinted and the Proceedings, including a report of the discussions, will be printed in 1962.

The provisional programme will be distributed through the co-operating institutions at the beginning of June, and the final programme and enrolment form will go out at the beginning of September.

Spring Meeting 1962

Welding for Power Generation

The theme of the Spring Meeting of 1962 which is to be held at Buxton from 1st to 3rd May, will be *Welding for Power Generation*. The following are examples of subjects on which it is hoped that papers will be offered, and members who would be willing to contribute papers on these or other subjects within the main theme are invited to send particulars to the Secretary before the end of March 1961.

Welding of boiler plant, headers, superheaters, etc., including nuclear heat exchangers
Welding of turbine and ancillary plant, including water turbines, cylinder casings, steam chests, valves, pumps, etc.
Pipework
Reactor pressure circuits including the pressure vessel, ducting, bellows units, etc.
Welding of rotors and shafts in turbo-alternators, water wheel alternators, etc.
Construction of tanks for transformers and switchgear
Welding of feed heaters and condensing plant
Welding of thick plate and sections
Suitability of new welding techniques and processes for power plant
Training of welders for Class I vessels
Inspection of welded plant by non-destructive methods
Welding in the fabrication of fuel elements including uranium, beryllium, zirconium, niobium, etc.
Welding in the repair and maintenance of power stations.

PUBLICATIONS

"*International Welding*"

Included with this issue of the Journal is the first quarterly supplement containing a selection from the documents issued for publication by the International Institute of Welding. These supplements will be reprinted and offered for subscription at 22*s* 6*d* a year (including postage) for the four issues, or 17*s* 6*d* a year to members of the Institute and other member societies of the International Institute of Welding.

The Institute often receives requests for copies of I.I.W. documents and has hitherto had to obtain these from Paris in duplicated form. It is therefore proposed to supply single copies of "*International Welding*", which is the name given to the supplement, at 5*s* to members of the Institute and other member societies of I.I.W., and to offer special reductions for bulk orders of a single issue which are placed at least two months before publication date.

The contents of the next supplement, to be published on 1st July, will be:

July 1961:
Reports of Commissions VIII–XIV.
Current Sources (Comm. XII)
Pressure Vessel Brittle Fracture (Comm. XI)

"*Radiographic Apparatus and Techniques*"

The Institute has just published, on behalf of the International Institute of Welding, its "Handbook on Radiographic Apparatus and Techniques", 80 pp. text with illustrations, price 16*s*, inclusive of postage. Orders should be addressed to the Secretary of the Institute

NEWS OF MEMBERS

Mr. J. D. Riddle, formerly manager of the Turbine Factory at the Rugby Works of Associated Electrical Industries Ltd., has been appointed Manager of a new Large Machine and Compressor Department at Rugby.

Headland Gauges Ltd. announce the appointment to their Board of Directors of Mr. J. H. Thornton and Mr. P. H. Van Klaveren. Headland Gauges Ltd. is the newly formed member of the Headland Group which is specializing in the manufacture of gauges, jigs and fixtures.

Mr. H. Martin, Home Sales Manager of Murex Welding Processes Ltd., Waltham Cross, Herts., retired in December 1960 on reaching retiring age after 38 years' service in the Company.

Mr. A. F. Gifford, who has recently been transferred to Associate Membership, has been appointed Welding Engineer at International Combustion Ltd., Derby, in succession to Mr. E. J. Keefe.

Mr. F. G. Hughes has been appointed Southern Sales Manager in the London Office of Robert Dempster & Sons Ltd. (Elland), at 57 Tufton Street, S.W.1. The appointment took effect from 2nd January 1961.

Mr. A. J. Francis, President of the South Western Branch, was elected an Honorary Member of the Institute in June 1957. The Secretary very much regrets that Mr. Francis's name was by mistake omitted from the list of honorary members in the printed List of Members recently issued.

Obituary

The Council records with regret the deaths of the following members:

Mr. J. S. Murray (West of Scotland, Assoc. Member 1940).

Mr. C. F. Jones (Wolverhampton, Assoc. Member 1938).

Mr. A. F. Newton, on 29th December 1960 (North London, Assoc. Member, 1952).

Mr. G. H. Oldfield, on 25th December 1960 (Sheffield, Member, 1942).

Mr. F. Parr, on 14th January 1961 (Manchester, Assoc. Member, 1943).

SCHOOL OF WELDING TECHNOLOGY

The following is a list of courses to be offered in the School of Welding Technology during May:

1st–4th May; D.37—Advanced Ultrasonic Inspection

15th–19th May; D.8/3—Welded Structures

29th–31st May; D.33—Co_2 Arc Welding

BRANCH NEWS

East Midlands — Pipelines

At the November meeting of the Branch, held in Derby on Tuesday, 15th, Mr. R. J. Wright presented a paper on "*Transportation Pipelines*".

The speaker opened his talk by saying that in an industry which is progressing so quickly it was difficult to choose a subject of general interest, yet sufficiently controversial to initiate the post-lecture discussions which, in his belief, enabled the most knowledge to be gained from any meeting of this kind.

Transportation costs are one of the major problems facing industry as a whole. This was particularly true in the petroleum, petro-chemical and gas-producing industries and pipelines could mean lower transportation costs.

Mr. Wright gave a brief history of the pipeline as a means of transporting liquids and gases, from the bamboo type used as much as 7,000 years ago by the Chinese to the present-day type.

In the United Kingdom the arc welding of pipelines was somewhat slower in developing than in the United States, because most commodities adaptable for transportation by pipeline could easily be moved by road tankers.

It was the great success of welding during the war, on such projects as Pluto, which, coupled with the immediate post-war expansion of the British petroleum and petro-chemical industries and the desire of the area gas boards up and down the country to increase the pressure passing through their mains, that really brought about the progress of welded construction in the United Kingdom to its present level of importance. Such progress depended entirely upon the welding engineer, who was ultimately responsible for training the welders to the high standard of efficiency required, and the skill of the operator in the field.

With the increase in use of pipelines, contractors looked for speedier welding means with reduced costs of pipeline construction. The way was now opened for the introduction of the American procedure of 'stovepipe welding'.

The speaker described the procedure and technique of stovepipe welding, stage by stage, illustrating this with slides. Stovepipe welding in Britain was successfully adopted due in considerable part to the patience and tolerance of the oil and gas industries and also of the contractors in the early stages. Stovepipe welding has since become the standard method of the major pipeline contractors in fabricating the many miles of pipelines which now extend throughout Great Britain and form such an important part of the gas and petroleum distribution system today.

A very interesting film called "Winfrith Pipeline" was shown, which showed the modern application of pipeline welding and construction techniques.

In the discussion that followed a large variety of questions were put to the lecturer, who dealt with them very carefully and capably. Comparisons were made between the British and American welders and British and American electrodes. The lecturer also explained why the standard of welding could vary.

In proposing a vote of thanks Mr. Haimes thanked Mr. Wright for the excellent paper and films that had been shown.

H.S-C

Leeds — Annual General Meeting

The Leeds and District Branch Annual General Meeting will be held on *18th April 1961* and not on 11th April, as previously announced.

Annual Dinner

The Annual Dinner of the Branch was held at the Hotel Metropole, Leeds, on Thursday, 8th December last. Mr. A. Robert Jenkins, J.P., Past President of the Institute responded to the toast of "The Institute of Welding", proposed by Alderman Sydney Hand, Deputy Lord Mayor of the City of Leeds. The toast of "The Guests" was proposed by Mr. H. T. Richardson, Leeds Branch Vice-Chairman and the response was made by the Reverend R. H. Talbot, Vicar of St. Edmunds. Among a large gathering of members and guests were Mr. G. A. Aldred, President of the Leeds Association of Engineers, Mr. J. Pidduck, Leeds College of Technology, Mr. S. B. Rippon, J.P., Chairman of the Sheffield Branch of the Institute and Mr. S. Stansfield, Managing Director of Oxley Engineering Co. Ltd. It was a most enjoyable evening.

Manchester — Automatic Welding

On 7th December 1960, Mr. J. A. Lucey lectured to the Branch on "*Automatic Welding*". The paper dealt

principally with four developments in automatic and semi-automatic arc welding which have been introduced into Great Britain within the last five years:

(i) Fusarc/CO_2 welding in which a continuous covered electrode is shielded by CO_2 gas. This is a British invention which has greatly extended the scope of automatic visible arc welding, particularly for horizontal/vertical fillet welding applications.

(ii) Multiple electrode submerged-arc welding—three different systems of this and their particular advantages were outlined:

(*a*) Parallel electrode welding in which two electrodes are fed on a single welding head and give approximately 50% speed increase.

(*b*) Multi-power tandem welding in which two welding heads and two separate power sources are used to give an increase in welding speed, two to two-and-a-half times faster than single electrode welding.

(*c*) Series arc welding which is a technique for cladding and surfacing in which two welding heads are employed and a single welding power source is connected across the two heads. Deposition rate per ampere is double compared with single electrode welding and dilution with the parent plate can be controlled to as low a figure as 10%.

(iii) Electro-slag welding. This process has been developed from the submerged-arc process in the U.S.S.R. and is now beginning to be used in Britain for heavy plate fabrication.

(iv) Semi-automatic welding with CO_2 shielding. The introduction of processes using a combined gas/flux shield, together with advance in power source design permitting the use of lower welding currents, have greatly extended the scope of semi-automatic welding of mild and low alloy steels.

A.C.M.

North London

Pipelines

On Wednesday evening, 14th December 1960, with Mr. C. A. Burton in the Chair, the North and South London Branches were privileged to hear a paper "*Welding of transportation pipelines*", presented by Messrs. Page and Richardson, in the absence of the author, Mr. R. J. Wright. Before dealing with welded pipelines, the subject of the paper, Mr. Page outlined the history of transportation by pipes, from bamboo to metallic pipes and finally to welded transportation pipes.

A thorough review was given of pipeline weldments from welder's qualifications to final acceptance tests on welded joints. A film augmented the *viva voce* exposition. The meeting was well attended. A vote of thanks was accorded the speakers for their interesting and thoroughly practical contribution to the furtherance of welding technology.

H.B.M.

Sheffield

Annual Dinner

There was a record attendance of over 250 members and guests, including many of the leaders of Sheffield industry, at the Annual Dinner of the Sheffield and District Branch at the Royal Victoria Hotel on 9th January.

Mr. Robert Jenkins, J.P., President of the Branch, was Chairman, and the principal guest was the Master Cutler, Mr. C. H. T. Williams, J.P., who proposed the toast of "The Institute of Welding and the Sheffield Branch" in a speech which stressed the rapid development of welding technology and the importance of the Institute's educational work.

In the absence of the President, Mr. E. Fuchs, who was prevented from attending by indisposition, the Secretary of the Institute, Mr. G. Parsloe, responded to the toast. He reviewed the progress of the Institute over the past eighteen years and spoke of the decision to establish a postgraduate course in welding technology at the College of Aeronautics, Cranfield, as a major break-through on the educational front. He urged all those who represented industry, whether as users of welding or as suppliers, to make sure that the course was properly supported by men from their own staff.

In response to the toast of "The Guests", which was proposed by the Branch Chairman, Mr. S. B. Rippon, J.P., Dr. R. Weck, Director of the British Welding Research Association, reinforced the Secretary's plea for industrial support for the new course in an emphatic speech which stressed industry's need for men with a thorough knowledge and understanding of the welding processes and their applications.

South London

Low Alloy Steel Welds

For the first meeting of the New Year on 11th January, Dr. W. E. Freeth of G. A. Harvey & Co. Ltd. gave a most interesting talk on the fundamental principles involved in welding low alloy steels. Some 38 members were present and in introducing the speaker, the Chairman, Mr. J. Hinde, welcomed members and visitors to the first session of 1961. Dr. Freeth examined first of all the principles of making sound welds in mild steel and in doing so he stressed the advances in welding technology that had enabled us to control more carefully the composition and consistency of the welding consumer goods. He noted that excess carbon content is still the main cause of cracking in mild steel and discussed the influence of sulphur and phosphorus.

Moving on to the low alloy steels he showed how certain elements were beneficial in increasing strength and weldability but at greater expense. He differentiated between the cracking tendencies of the weld and heat affected zone and suggested the influential elements in cases of hot and cold cracking.

During the discussion, contributors referred to the welding of Cr – Mo – V steels and the stressing of welds.

After a very thorough handling of his subject Dr. Freeth was rewarded with much applause from his audience.

N.T.E.

South Western

Welding Forum

The welding Forum, now firmly established as a popular annual event, was held on 5th December at Radiant House, Bristol.

The Panel, which was under the chairmanship of Mr. T. M. B. Sessions (Messrs. Fielding & Platt Ltd.) consisted of Dr. C. L. M. Cottrell (Bristol Aerojet Ltd.), Dr. W. E. Freeth (G. A. Harvey & Co. (London) Ltd.), Mr. L. B. Smith (British Oxygen Co. Ltd.) and Mr. E. M. Wilson (Bristol Aerojet Ltd.).

Dr. Cottrell kindly agreed at short notice to be seconded to the panel by the chairman in the absence of Mr. G. Foster (Stothert & Pitt Ltd.), who unfortunately was beset with flood problems, his works at the time being under approximately 5 ft of water.

A variety of questions was dealt with, commencing with the effect of the many automatic welding processes on the skill of the welding operator, the Panel's opinion being that a different type of skill was needed here which should be acknowledged by a certified grade of operator for automatic welding. The joining of cast iron to mild steel was discussed, as were electrodes for welding cast steel and also the correct application of low-hydrogen and iron powder electrodes.

Methods of weld inspection and standards to work to were dealt with comprehensively. On the light-alloy side, for example, it was pointed out that BS.1600, Pt.3, at present in the course of preparation, would give a valuable and much needed guide in the manufacture by welding of aluminium alloy pressure vessels. The types and causes of weld defects in aluminium alloy welds were shown and examples were given.

The difficulties to be encountered in the use of the ultrasonic method of inspection for steel welds was dealt with, and the Panel felt that, now developments were taking place to enable an image to be viewed directly on a screen, this method of inspection might find greater application in the welding industry than hitherto.

The question of when or when not to prepare edges, with particular reference to web plate girders, was also discussed and it was agreed that the least edge preparation possible with the maximum use of automatic welding would give the best results.

A vote of thanks was given by Mr. T. E. Erickson (Rockweld Ltd.), and in reply the Chairman, Mr. Sessions, thanked the members of the audience for the variety and flow of questions put to the Panel.

E.M.W.

West of Scotland

Electro-Slag Welding

A General Meeting of the Branch was held on Wednesday, 21st December 1960, at 7 p.m., in the Institution of Engineers and Shipbuilders in Scotland, Glasgow C.3, and was attended by 63 members and visitors.

A paper entitled "*Electro-slag welding*" was presented by Mr. A. M. Horsfield, A.I.M.

Introducing his subject with the aid of lantern illustrations the speaker next proceeded to describe the process stage by stage through its development.

Points of interest were the absence of 'arc-energy' after the weld had been started, the important function of the slag in ensuring penetration, current densities and pressures, the effect of heat input on parent plate and weld, and methods of pre-heat, post heat, and stress relieving. The general physical analysis of the weld deposit, together with a comparison of the continental method of assessing the weld, were all discussed. Reference was also made to the minimum plate thickness suitable for this process.

In the discussion which followed seven members took part, and had their questions answered to the satisfaction of the Meeting.

H.H.M.

Wolverhampton

Metallurgy without tears

A number of students were among those present at a lively and entertaining meeting on 7th December, and Mr. Fullwood's paper might well have been subtitled "*Metallurgy without Tears*". His aim was to introduce the science of metallurgy, and particularly physical metallurgy in its fundamental form, and then to explain some well-known welding phenomena such as hydrogen embrittlement and brittle fracture in terms of lattice structure.

Mr. Fullwood stated that when metals solidify they crystallize with random orientation and grain boundaries into three alternative patterns:

(i) Body centred cubic lattice; *e.g.* hard metals such as molybdenum, iron, tungsten.
(ii) Face centred cubic lattice; *e.g.* low melting point malleable metals such as lead.
(iii) Hexagonal lattice; *e.g.* hard, brittle metals such as titanium, manganese, zinc, copper.

These contained respectively 2, 4 or 6 atoms per unit cell, and by X-ray diffraction techniques introduced by Sir Lawrence Bragg it was possible to determine the spacing of these atoms in terms of Ångström units (10^{-8} cm).

As an example of the use of this technique, Mr. Fullwood showed how it was possible to calculate the density of a material in terms of its atomic weight, Avogadro's Number, and the lattice structure and its inter-atomic spacing. For example iron, having a body centred cubic lattice structure (with 2 atoms per unit cell), an atomic weight of 55·85 and an atomic spacing of $2{\cdot}86 \times 10^{-8}$ has a density of:

$$D = \frac{M}{V} = \frac{2 \times 55{\cdot}85}{6{\cdot}023 \times 10^{-23}} \div (2{\cdot}86 \times 10^{-8})^3$$
$$= 7{\cdot}9 \text{ g/cu.cm}$$

The temperature at which recrystallization takes place varies from metal to metal. Molybdenum has the second highest (870°C.) and hence its use in creep resisting applications. At the other end of the scale lead recrystallizes below room temperature, and it is therefore self-annealing—a fact which is made use of in shielding against atomic radiation since any radiation embrittlement is automatically annealed out.

Mr. Fullwood concluded his paper by describing the mechanism by which the introduction of hydrogen into a melt of steel, such as when weld metal was solidifying, gives rise to discontinuities in the lattice structure which cause transgranular brittleness.

During the discussion a number of highly technical questions were asked by some of the metallurgists present, and it soon became obvious that the science of metallurgy was not quite as simple as Mr. Fullwood had lead his audience to believe. However, Mr. Fieldhouse expressed the views of all those present in thanking a past Wulfrunian for an interesting and enjoyable talk. He looked forward to the publishing of Mr. Fullwood's book and was sure that it would have a wide circulation.

B.K.B.

INTERNATIONAL INSTITUTE OF WELDING

1961 Annual Assembly

A good attendance is expected at the first Annual Assembly of the International Institute of Welding to be held outside Europe, which opens in New York on 10th April and partially overlaps with the Spring Meeting of the American Welding Society there in the following week.

Nearly every seat has been booked on the charter plane which is to carry members of the European delegations and will leave on 9th April from Paris and London. The United Kingdom delegation will be headed by Mr. Robert Jenkins, Dr. R. Weck, and Mr. G. Parsloe, the Secretary General of the International Institute.

The programme will follow the usual pattern and will include a formal opening session, meetings of the Governing and Executive Councils at the beginning and end of the Assembly, the Houdremont Lecture, and four days devoted to meetings of the fifteen Technical Committees and their Drafting Committees. There will not, this year, be any form of Public Session, because participants at the IIW Assembly have been invited to attend the Spring Meeting of the American Welding Society, which is to be held in conjunction with the IIW Assembly, from 17th to 21st April.

The programme for the AWS Meeting and Welding Exposition will include the Adams Lecture by Mr. H. Granjon (France), two educational lectures by Professor Rykalin (USSR), and twenty-two technical sessions at which sixty-six papers will be presented and discussed. Among these papers will be nine by European members of the following Commissions of the IIW: I, II, III, V, IX and X, XI, XII, XIII, XV.

Provision has also been made for two all-day inspection trips including visits to four industrial plants and laboratories in the New York area and, on the invitation of the Canadian Council of the IIW, for an all-day trip by chartered aircraft to the Buffalo-Niagara Falls, which include visits to industrial plants. No provision has, this year, been made for post-Assembly industrial tours, but the American delegation has offered to assist delegates in planning additional industrial and scientific visits, should they so desire.

CONFERENCES, COURSES and EXHIBITIONS

Fracture of Metals

A vacation course on the Fracture of Metals is to be held at Battersea College of Technology (Metallurgy Dept.) from 11th to 14th April 1961. The fee is £10 10*s* 0*d* inclusive of refreshments.

Enrolment forms may be obtained from the Secretary (Metallurgy Courses), Battersea College of Technology, London, S.W.11.

Mechanics of Rupture

A conference on the Mechanics of Rupture has been organized by the Stress Analysis Group of the Institute of Physics and the Physical Society. It will be held in the Department of Physics at Southampton University from 24th to 27th April 1961.

Full details can be obtained from L. Lawrence, Esq., Institute of Physics and the Physical Society, 47 Bedford Square, London, S.W.1.

Electrical Engineers Exhibition

The tenth A.S.E.E. Exhibition is being held at Earl's Court, London, S.W.5 from 21st to 25th March 1961.

Engineering Exhibition

The Engineering, Marine, Welding and Nuclear Energy Exhibition is being held again this year at Olympia, from 20th April to 4th May. Many welding supply manufacturers will be displaying completely new ranges of equipment.

NEWS FROM INDUSTRY

Corrosion and welding engineering

The services provided by Welding Supervision Ltd. and Cathodic Corrosion Control Ltd. (wholly owned subsidiaries of Constructors John Brown Ltd.) have been amalgamated and will now be provided by a single company—Corrosion and Welding Engineering Ltd.—which started operation on 1st January 1961.

BOC training college

The British Oxygen Co. Ltd. has opened a staff training centre at Chartridge Lodge, near Chesham, with Lt.-Col. T. O'G. Cochrane as Principal.

Courses of 2–4 weeks will be residential and will at first be organized for senior and middle levels of management. A wider field will be covered later and it is hoped to start courses for foremen and supervisors by the end of 1962.

Pre-treatment of metals

A fourth division—the Metal Industries Division—has been initiated by Diversey (U.K.) Ltd. to handle a range of materials for the preparation of metals before further processing. These Aluminux compounds are used particularly for the cleaning of aluminium and its alloys before resistance welding, anodizing or other surface treatments.

Transport research laboratory

The new Chiswick research laboratory of London Transport was officially inaugurated at the end of 1960. It has enabled the scientific staff of the research department to be brought together under one roof for the first time and it will be the centre for the scientific control and investigation of materials and equipment used throughout London Transport's road and rail services. It also gives space for important new facilities and equipment as well as additional staff.

The facilities include a cold chamber for low-temperature testing of materials, a specially-designed, screened room for radiographic work, heat-treatment furnaces and welding equipment, a pilot plant laboratory, special recording equipment for strain gauge tests, and a fatigue testing machine for railway car axles.

The availability of heat-treatment furnaces and welding equipment enhances the value of advice given to the engineering departments on metallurgical problems by augmenting existing facilities for such investigations.

The greatest expansion is in the facilities now available for research devoted to engineering problems. In recent years much work has been done in assisting the engineering departments in the investigation of problems—notably by the application of strain gauge techniques—and this side of the work has been greatly strengthened by the acquisition of further equipment. Equally important, provision has now been made for major engineering research to be carried out within the laboratory itself.

In the first instance, attention will be concentrated on work with a machine for studying fatigue in railway axles which has been designed and constructed under an extra-mural research contract by the Mechanical Engineering Department of the University of Nottingham. Ample space has been allowed for the expected growth in the engineering aspects of the laboratory's activities.

Inspection of pressure plant for nuclear installations

Lloyd's Register of Shipping have announced the publication of recommendations for the design, manufacture and testing of pressure components of land based nuclear installations.

The Society, through its Land Division, has been closely associated with the survey and inspection of such pressure components from the early stages of the development of nuclear energy in the United Kingdom. During this time Lloyd's Register has undertaken the inspection of the pressure plant of the Calder Hall and Chapelcross power stations, and is currently engaged with similar responsibilities for five civil nuclear power stations, which are modified and larger versions of the Calder Hall prototype, and which are now under construction in this country, in Italy and Japan.

The Society is also actively engaged on prototype installations such as the advanced gas cooled reactor being built at Windscale for the United Kingdom Atomic Energy Authority, and the Dragon project which is being constructed at Winfrith Heath under the auspices of the Organization for European Economic Co-operation. On the development of reactor installations suitable for marine nuclear propulsion the Society recently published Provisional Rules for the Classification of Nuclear Ships.

At various times over the last 10 years Lloyd's Register has made recommendations for the design, construction and testing of land based nuclear components, and issued preliminary notes for the guidance of manufacturers in 1957. The rapid development of nuclear engineering has, however, necessitated the continuous review of these recommendations in the light of experience gained, and the Society now considers it timely to publish them in an up-to-date and comprehensive form to cover the nuclear reactor systems at present being built or projected. It is intended to review and supplement these recommendations as further experience is gained.

Copies of the publication, "Survey of Pressure Components for Land Based Nuclear Installations—Provisional Requirements 1960", are available at a cost of 3 guineas on application to Lloyd's Register of Shipping, Land Division, Norfolk House, Croydon.

BCAC Chairman gives inaugural luncheon

The Secretary, Mr. G. Parsloe, represented the Institute of Welding at a luncheon held on 7th December 1960 at the Waldorf Hotel to mark the recent reconstitution of The British Conference on Automation and Computation, given by its Chairman, Sir Walter Puckey.

Sir Walter recalled that the objects of the BCAC were: (*a*) To stimulate interest in, to spread knowledge of, and to foster development and applications of automatic control and computations. (*b*) To afford a common meeting ground for the adhering organizations whereby such of their activities as fall within the purview of the Conference can, if they so desire, be co-ordinated and extended (*c*) To encourage and, if desired, to co-ordinate, the presentation at International Conferences of British papers whose subjects fall within the purview of the Conference. (*d*) To maintain, as may be desirable, liaison with other countries which support such International Conferences.

The BCAC had decided to set up three Panels to activate the following aspects of its work:

Education and Training—Chairman, Professor G. D. S. MacLellan (University of Glasgow)

Research and Development—Chairman, Mr. J. F. Coales (University of Cambridge)

Public Relations—Chairman, Mr. W. C. F. Hessenberg (Deputy-Director, British Iron & Steel Research Association).

Arrangements were well advanced for the holding of a Conference at Harrogate from 27th to 30th June 1961, with the general title "Automation—Men and Money."

Plans were also in hand for the delivery, in the autumn of 1961 of the first BNAC Annual Lecture, which would be in the form of an authoritative review, by an expert in the field, of the present position and probable future development, of automation procedures in British industry and commerce.

NEW PUBLICATIONS

Welded pipe spires

Our cover illustration shows the erection of one of a series of tetrahedral shaped supports for the 17 spires of the U.S. Air Force Academy chapel at Colorado Springs. The 75ft. long frames are fabricated from 4 in. and 6 in. dia. steel pipe made by the Republic Steel Corporation. The contractors were the Mississippi Valley Structural Steel Company.

Welding charts

The second of a new series of Sifbronze welding data and instruction charts, recently issued, gives conversion factors and tables, temperature scales, flame temperatures, gas values, melting points of metals, and welding data for fusion welding and Sifbronze welding mild steel. The chart also includes illustrations of common defects in welding and typical forms of welded joint.

Copies of the chart, at 2*s*. each can be obtained from The Suffolk Iron Foundry (1920) Ltd., Stowmarket, Suffolk.

Aluminium extrusions

Imperial Aluminium Co. Ltd., which draws from the combined production resources and technical experience of ICI and the Aluminium Company of America, has recently issued a two-part catalogue of extruded 'Impalco' aluminium and aluminium alloy sections. These catalogues give full details of dimensions and weights of a wide range of sections, grouped according to shape or to end use. An accompanying leaflet illustrates some of the many applications of extruded and drawn Impalco products.

New Periodical on Heat and Mass Transfer

The first issue of a new journal "International Journal of Heat and Mass Transfer" appeared in June last. The Board of Editors is composed of six experts from the United States, Germany, the U.S.S.R. and Great Britain, and there is a widely representative Advisory Board, headed by Professor E. R. G. Eckert of the University of Minnesota and Professor O. A. Saunders of Imperial College, London, as co-chairman.

There is a valuable bibliography of Heat Transfer prepared at the Laboratory of the University of Minnesota, and ten papers on various aspects of Mass Transfer, printed in the original languages, English, French and German.

The journal is published by the Pergamon Press Limited and the subscription rates are £7 per volume for libraries, etc. and £5 5*s*. 0*d*. for individuals.

DIARY

1st Mar. — Manchester — "*Methods adopted by a large user when purchasing welded equipment*" by E. Fuchs and W. Ashworth (Reynolds Hall, College of Science and Technology, Manchester, 7.15 p.m.)
North London—Visit to Enfield Rolling Mills Ltd.
Institution of Structural Engineers—"*The design, fabrication and erection of welded girders for the South Durham Steel and Iron Co. Ltd.*" by W. G. Gentry (Neville Hall, Newcastle, 6.30 p.m.)

2nd Mar.—N.E. Tyneside—"*The work of B.W.R.A.*" by H. F. Tremlett (Mining Institute, Newcastle, 7.0 p.m.)
South Wales—"*Welding in marine engineering*" by J. A. Dorrat (Institute of Engineers, Cardiff, 7.0 p.m.)

3rd Mar.—South Wales—"*Welding in marine engineering*" by J. A. Dorrat (Technical College, Swansea, 7.0 p.m.)

4th Mar.—N.E. Tyneside—Visit to Clarke, Chapman & Co. Ltd., Gateshead

6th Mar.—Manchester—Annual Dinner (Grand Hotel, Manchester)
South Western—"*Non destructive testing*" by H. Gibbs (Radiant House, Bristol, 7.15 p.m.)

7th Mar.—Institution of Structural Engineers—"*The design, fabrication and erection of welded girders for the South Durham Steel and Iron Co. Ltd.*" by W. G. Gentry (Cleveland Scientific and Technical Institution, Middlesbrough, 6.30 p.m.)

8th Mar.—Preston—"*Recent developments in U.S.S.R.*" by Dr. D. S. Galloway (Harris Technical College, Preston, 7.15 p.m.)
South London—"*The testing, inspection and assessment of welds*" by C. Atkinson (54 Princes Gate, S.W.7, 7.30 p.m.)
East of Scotland—"*Electric pre-heating and stress relieving*" by R. McGlashan (25 Charlotte Square, Edinburgh, 7.30 p.m.)

9th Mar.—Eastern Counties—Film Show (Ipswich Civic College, 7.30 p.m.)

11th Mar.—Wolverhampton—Visit to Hilton Main Colliery, Staffs.

13th Mar.—N.E. Tees-side—"*Ferrous welding metallurgy*" by T. E. M. Jones (Cleveland Scientific and Technical Institution, Corporation Road, Middlesbrough, 7.30 p.m.)
Sheffield—"*Heat-affected zone cracking in austenitic chromium–nickel steels*" by H. F. Tremlett (Grand Hotel, Sheffield, 7.0 p.m.)

13th–17th Mar.—School of Welding Technology — Course D17/1, Advanced Course for Welding Engineers

14th Mar.—Liverpool—"*Welding and the draughtsman*" by H. B. Merriman (College of Technology, Byrom St., 7.15 p.m.)

15th Mar.—West of Scotland—"*Electric pre-heating and stress relieving*" by R. McGlashan (Institution of Engineers and Shipbuilders, 39 Elmbank Crescent, Glasgow, C.2, 7.0 p.m.)
Wolverhampton—"*The prospect for gas-shielded welding*" by A. A. Smith (Wulfrunians Club, 7.30 p.m.)

16th Mar.—Southern Counties—"*Lead burning, etc.*" by L. B. Smith (Technical College, Southampton)
Leeds—"*Bridge structures*" by E. R. Bowers (Hotel Metropole, Leeds, 7.30 p.m.)

17th Mar.—Birmingham—"*Economic aspects of various fusion welding processes*" by W. D. Waller (Grand Hotel, Birmingham, 7.30 p.m.)

21st Mar.—Eastern Counties—"*Pipeline welding*" by R. Wright (Ipswich, Electric House, 7.30 p.m.)

22nd Mar.—South London (Medway)—"Brains Trust" (Sun Hotel, Chatham, 7.30 p.m.)
Birmingham — Visit to Hereford Works of Henry Wiggin & Co. Ltd.
North London—"*The design of resistance welding equipment for unusual applications*" by J. D. Morris (54 Princes Gate, S.W.7, 7.30 p.m.)

24th Mar.—South Wales—Annual Dinner (Angel Hotel, Cardiff)

27th–29th Mar.—School of Welding Technology—Course D28/1, Welding for Junior Management

30th Mar.—West of Scotland—Visit to the Fairfield Shipbuilding & Engineering Co. Ltd., Glasgow

4th April—East Midlands—Annual General Meeting and films (Nottingham)
North London (Slough Section)—"*Electrical characteristics of welding plant*" by J. C. Needham (Lecture Room, Community Centre, Farnham Road, Slough, 7.30 p.m.)

Current WELDING LITERATURE

Book Reviews
Additions to the Institute Library
Trade Publications

CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

Canadian Welder, 1960, vol. 51, November

Welding aluminium, R. R. Kottmeier (10–15)
Furnace brazing cuts costs (16–17)
Welding technology in Russia (20, 22)

Journal of the Japan Welding Society, 1960, vol. 29, October

Continuous cooling transformation diagrams of steels for welding and their application, H. Sekiguchi and M. Inagaki (3–12)
Heat conduction theory including melting state, T. Sato (13–24)
Cooling time and brittleness of various steels submitted to welding (Report 6), H. Sekiguchi and others (25–30)
Cooling rates in stainless steel welds, H. Kihara and others (31–37)
Welding of cast iron and nodular graphite cast irons (Report 1), M. Homma and others (38–44)
Study on applicable electrodes for 19-9DL heat resisting steel, Y. Ito (45–51)

Przeglad Spawalnictwa (Poland), 1960, vol. 12, December

Welding of boiler elements, K. Kajzer
Statics and construction of glued metal joints, R. Brzozowski

Przeglad Spawalnictwa (Poland), 1961, vol. 13, January

Essential problems of welding development in Polish industry, Z. Szczecinski
Methods of testing glued metal joints, R. Brzozowski
Thermit fusion welding procedure in rail joining on Polish railways. Part 1, L. Nekanda-Trepka

The Stabilizer, 1960, vol. 27, Autumn

Scotland's gas supergrid (6–9)
Tubular fabrication. Part 4, A. Scott (10–12)
Two new underwater pipelines completed in South Wales (15–16)

Welding and Metal Fabrication, 1960, vol. 28, December

Magnetic force welding, C. A. Rowlands (474–481)
Fabrication in Canada, G. J. Foster (482–490)
Recent work on pressure welding, R. F. Tylecote (491–494)
The application of steel extrusions, R. D. C. Jones (495–498)
Manipulation of metals (499–502)
Fabricated high duty boilers (503)

Welding Engineer (U.S.A.), 1960, vol. 45, November

Welded studs help to double floor load capacity, I. G. Cantor (38–39)
Fundamentals of projection welding, D. D. Williams (40–42)
Welded cars travel on welded carriers (43)
Oxyacetylene pressure welding of rail arrives at the push-button stage (44–45)
Tig welding joins small stainless tubes to thick tube-sheet, J. M. Gerken and D. B. Kittle (46–48)
Carbon, stainless steel welded in fabrication of centrifugal mills (50–51)
Welded design, process control guarantee better products, W. C. Nemitz (52, 54)
Oxygen is neither combustible nor explosive, often miscalled, F. C. Saacke (58–59)
Brazing produces smooth surfaces for cab doors, G. A. Medsker (60, 62)
Minnesota bridge submerged-arc welded, A. Hanson and W. G. Fess (63–64)

Welding Fabrication and Design (Australia), 1960, vol. 4, October

The metallurgy of chromium–nickel austenitic steel welds, I. J. Ferris (9–17)
Design considerations in welded ship construction, R. F. Pearce (19–23)
Welding applications at Mount Isa Mines Ltd., S. A. Eyers (23–31)
Industrial radiography, G. F. MacKnight (31–37)
Overseas developments and trends in welding, W. Bernard (37–44)

Welding Journal (U.S.A.), 1960, vol. 39, December

Evaluation of weld quality on a submarine pipeline, P. W. Turner (1215–1221)

New techniques for cladding with the gas shielded process, R. D. Engel (1222–1229)

Inert-gas shielded metal-arc spot welding of aluminium, S. E. McFall (1230–1236)

Welding of large rocket motors, J. E. Bartley and R. E. Frala (1237–1243)

Fusion-zone structures and properties in aluminium alloys, P. E. Brown and C. M. Adams (520*s*–524*s*)

Analytical investigation of residual stresses and distortions due to welding, K. Masubuchi (525*s*–537*s*)

Design of interior columns in multi-storey frames, J. S. Ellis (538*s*–542*s*)

A reversed-bend test to study ductile to brittle transition, J. H. Ludley and D. C. Drucker (543*s*–546*s*)

Current welding research problems (547*s*–552*s*)

Welding News (Australia), 1960, folio 103, July

Flame washing, the economic way of removing excess metal (2–3)

The wide scope of portable cutting machines (4–5)

The facts of flame gouging (18–19)

Backing bar jigs for inert gas welding (20–21)

Welding News (Australia), 1960, folio1 04, October

Machine flame cutting as a modern production tool (2–4)

How weldable is S.G. iron? (5–7)

Fine wire welding of thin materials (9–10)

Argonaut steel welding with Argon/CO_2 mixtures (15–16)

Arc weldability of common materials (table) (17)

Groove-arc for A.C. (18–19)

"Hi-Speed" machine cutting nozzles for oxyacetylene or oxy-handigas (20–21)

Welding Research Abroad (U.S.A.), 1960, vol. 6 November

Automatic argonarc welding of stainless steels with consumable electrodes, A. N. Akulov and N. Yu. Pak'chuk (Translated from *Svarochnoe Proizvodstvo* June 1956, pp. 27–29) (53–58)

On the mechanism of hot cracking of welds, V. A. Toropov (Translated from *Metallovedenie I Obrabotka Metallov*, June 1957, pp. 54–58) (59–68)

Wiggin Nickel Alloys, 1960, No. 59

Comparison of properties of weldments in Nimonic heat-resisting alloys in sheet form (18 s.w.g., 0·048 in., 0·12 mm.) (8–9)

Air-cooled heat-exchangers (13–15)

Zeitschrift für Schweisstechnik (Switzerland), 1960, vol. 50, September

Large, up-to-date oxyacetylene cutting machines, M. Maier (268–272)

Applications of welding in the construction of gas turbines, Part 2, A. Luthy (273–276)

Report on an investigation of PVC welded assemblies, A. Hermann (277–285)

Zeitschrift für Schweisstechnik (Switzerland), 1960, vol. 50, October

The welding of aluminium and aluminium alloys in the construction of atomic reactors, C. G. Keel (298–301)

Large up-to-date oxy-acetylene cutting machines, Part 2, M. M. Maier (308–315)

Zeitschrift für Schweisstechnik (Switzerland), 1960, vol. 50, December

Batteries of cylinders for liquid acetylene—possibilities and advantages (368–372)

Electronic control of resistance welding machines, F. Gallmann (373–386)

Maintenance and repair by welding in heavy industry. Part 2 (386–389)

Zvaranie (Czechoslovakia), 1960, vol. 9, September

New oxygen cutting machines at the Brno Fair, P. Subrt (253–255)

Automatic and semi-automatic welding machines for CO_2-shielded welding, K. Rejchlik (256–257)

Exhaust equipment in welding shops, V. Hromadko (258–260)

Contribution to the question of welding steels of different structural basis (Conclusions), V. Pilous (260–263)

Contribution to the evaluation of weld metal resistance to pore development with under-flux welding, J. Vana (263–264)

Strength of welded joints stressed under alternative rotating bend tests with the application of various welding methods, P. Galan and P. Jozefini (266–269)

Fighting against weariness caused by manual welding, J. Vodera (269–271)

Three-phase current welding, F. Formanek (271–273)

Zvaranie (Czechoslovakia), 1960, vol. 9, October

Shielded arc welding of economic stainless nickel-free austenitic steels of the CrMnN type, K. Lobl and A. Kabrhel (286–290)

The question of the start with electro-slag welding, M. Mosny (290–293)

Equipment for electro-slag welding beneath boiler drums, O. Hajzler (294–295)

Repair of high-pressure hydrogenation reactor shells, damaged by bomb splinters during bombardment, R. Halbich (296–301)

Contribution to questions of terminology in automatic welding, M. Mosny (313–316)

Zvaranie (Czechoslovakia), 1960, vol. 9, November

Soviet welding techniques—a help to technical progress (317–320)

The development of hard-surfacing alloys of the Co–Cr–Mo–W type for service in the temperature range of 700°C (320–326)

The question of the start in electro-slag welding. Part 2, M. Mosny (326–330)

The problems of electrode holder improvement, B. Stanek (330–335)

A new electrode holder, B. Vrana (335–336)

New pinch welder type, B. Vrana (336–337)

Earthing of the welding cable, I. Hrubisek (339)

Zvaranie (Czechoslovakia), 1960, vol. 9, December

The importance of welding for technical development, A. Zapletalek (349–350)

The use of radioisotopes in investigating problems occurring with welding, B. Zitnansky (350–353)

Small adaptations of KP-60 suspension pliers enable threefold acceleration of the working process, L. Pliva (354–356)

Furnace brazing in an exothermic atmosphere, O. Moravek (357–362)

Flame straightening and its economical use in manufacture, B. Vrana (362–364)

Welding with horizontal electrodes, A. Hecl (364–365)

Tack welding of components, R. Krnak (366–368)

Other Journals

Fabrication aspects of Canada's NPD reactor, by G. W. Platt and W. J. Burns (*Machine Production* (Canada), 1960, vol. 19, September, pp. 29–32; 49)

The vertomatic electro-slag process of welding, S. G. Maine (*Engineer and Foundryman* (South Africa), 1960, vol. 26, August, pp. 20–28)

The corrosion of welded steel pump column piping handling acid mine waters, F. P. A. Robinson (*Engineer and Foundryman* (South Africa), 1960, vol. 26, August, pp. 29–32)

Problems of welding high temperature steel. Part 2, by E. P. Kauhausen and others (*Werkstatt und Betrieb* (Germany), 1960, vol. 93, October, pp. 653–661)

Modern welding engineering. Important realization for large-scale and small-scale manufacturing works, by E. Sudasch (*Werkstatt und Betrieb* (Germany), 1960, vol. 93, October, pp. 662–666)

Line forms structural members at joist-per-minute rate, C. F Kaunitz and C. H. Guenther (*Iron Age* (U.S.A.), 1960, vol. 186, September 22, pp. 97–99)

Welded penstocks for hydro-electric power stations. Materials, electrode composition, welding, weld testing, ultrasonic inspection, field workshop, and erection, by J. Bienz (*Pipes and Pipelines*, 1960, vol. 5, October, Pipeline Engineering section, pp. ii–viii)

Pipe branch connection, by P. H. R. Lane (*Engineering*, 1960, vol. 190, 7 October, pp. 490–492)

The cost of overwelding, P. Lynch-burns (*New Zealand Engineering*, 1960, vol. 15, August 15, pp. 294–295)

Maintenance welding, by W. H. T. Svanoe (*Mechanical Engineering* (U.S.A.), 1960, vol. 82, September, pp. 64–66)

Space-age beryllium: its technology, by R. H. Gassner (*Metal Progress* (U.S.A.), 1960, vol. 78, September, pp. 88–92)

Production procedures at the Beacon Works of John Thompson Motor Pressings Ltd. Part 1 (*Sheet Metal Industries*, 1960, vol. 37, October, pp. 718–728)

Nondestructive testing of hardware for solid rocket motors, by S. M. Joseph (*Nondestructive Testing* (U.S.A.), 1960, vol. 18, September–October, pp. 315–318)

Helium leak testing fuel rods for the PWR blanket, by A. E. Oaks (*Nondestructive Testing* (U.S.A.), 1960, vol. 18, pp. 319–322)

Fatigue of welded structures (*Commonwealth Engineer* (Australia), 1960, vol. 48, August, pp. 38–40)

Machine gouging cuts welding costs (*Commonwealth Engineer* (Australia) 1960, vol. 48, August, pp. 40–41)

A new safety device (for automatic reduction of the open-circuit voltage of a welding transformer) for protecting the welder, J. Lisser (Smit Mededlingen (Holland), 1960, vol. 15, April–June, pp. 34–43)

Quenched and tempered steels for welded structures and vessels, by J. Lessells (*Alloy Metals Review*, 1960, vol. 9, September, pp. 2–8)

Welding heavy bases for bridge towers, G. M. Mills (*Machine Production* (Canada), 1960, vol. 19, October, p. 39)

Designing for spot welding aluminium alloys (*Mechanical World*, 1960, vol. 140, November, pp. 470–471)

New brazing technique solves fitup problem (*Steel* (U.S.A.), 1960, vol. 147, October 24, p. 110)

Welded penstocks for hydro-electric power stations. 2. Examples of Sulzer penstocks: Field workshops: Erection (*Pipes and Pipelines*, 1960, vol. 5, November, pp. 31–34)

How to choose the right joint in shaft-to-plate unions, F. Strasser (*Iron Age* (U.S.A.), 1960, vol. 186, October 27, pp. 102–104)

Strip heat exchangers in three metals (*Engineering*, 1960, vol. 190, November 11, p. 634)

The 16 in. E.R.W. Tube Plant, Shotton, W. T. Brooks and others (*The Structural Engineer*, 1960, vol. 38, November, pp. 334–345)

Stiffening girders of two suspended light metal footbridges at Alpnach, Switzerland, K. Sutter and A. M. Mackie (*The Structural Engineer*, 1960, vol. 38, November, pp. 353–361)

New units speed rail welding (*Iron Age* (U.S.A.), 1960, vol. 186, October 20, p. 161)

Scanner avoids voltage drop in giant welding line (*Iron Age* (U.S.A.), 1960, vol. 186, October 20, pp. 164–166)

Pressure welds cut railroad costs (*Steel* (U.S.A.), 1960, vol. 147, October 17, p. 138)

Four ways stud welding pays off (*Steel* (U.S.A.), 1960, vol. 147, October 31, pp. 68–69)

Manual spotwelders fasten wind tunnel lining (*Steel* (U.S.A.), 1960, vol. 147, October 31, p. 78)

Repairers' guide to current motor bodies: Renault Dauphine (*Institute of Automobile Assessors Journal*, 1960, vol. 11, October, pp. 49–52)

Marine machinery failures, H. N. Pemberton (*Transactions of the Institute of Marine Engineers*, 1960, vol. 72, October, pp. 377–392. Discussion, pp. 393–403)

Novel techniques for surfacing with stainless steel (*Commonwealth Engineer*, 1960, vol. 48, September, pp. 39–40)

Re-siting an aircraft hangar, R. B. Burton (*New Zealand Engineering*, 1960, vol. 15, September, pp. 341–344)

L.A's new automatic aluminium pipewelder (*Liquid Air Review* (Canada), 1960, vol. 10, July, p. 11)

Aluminium welding and manipulation—Swedish methods U. Alfredsson (*Nuclear Engineering*, 1960, vol. 5, September pp. 405–408)

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The Register of the Gas Industry 1960, Hertfordshire, Gas Publications Ltd., 1960

SELL'S *British Aviation* 1960, London, Business Dictionaries Ltd., 1960

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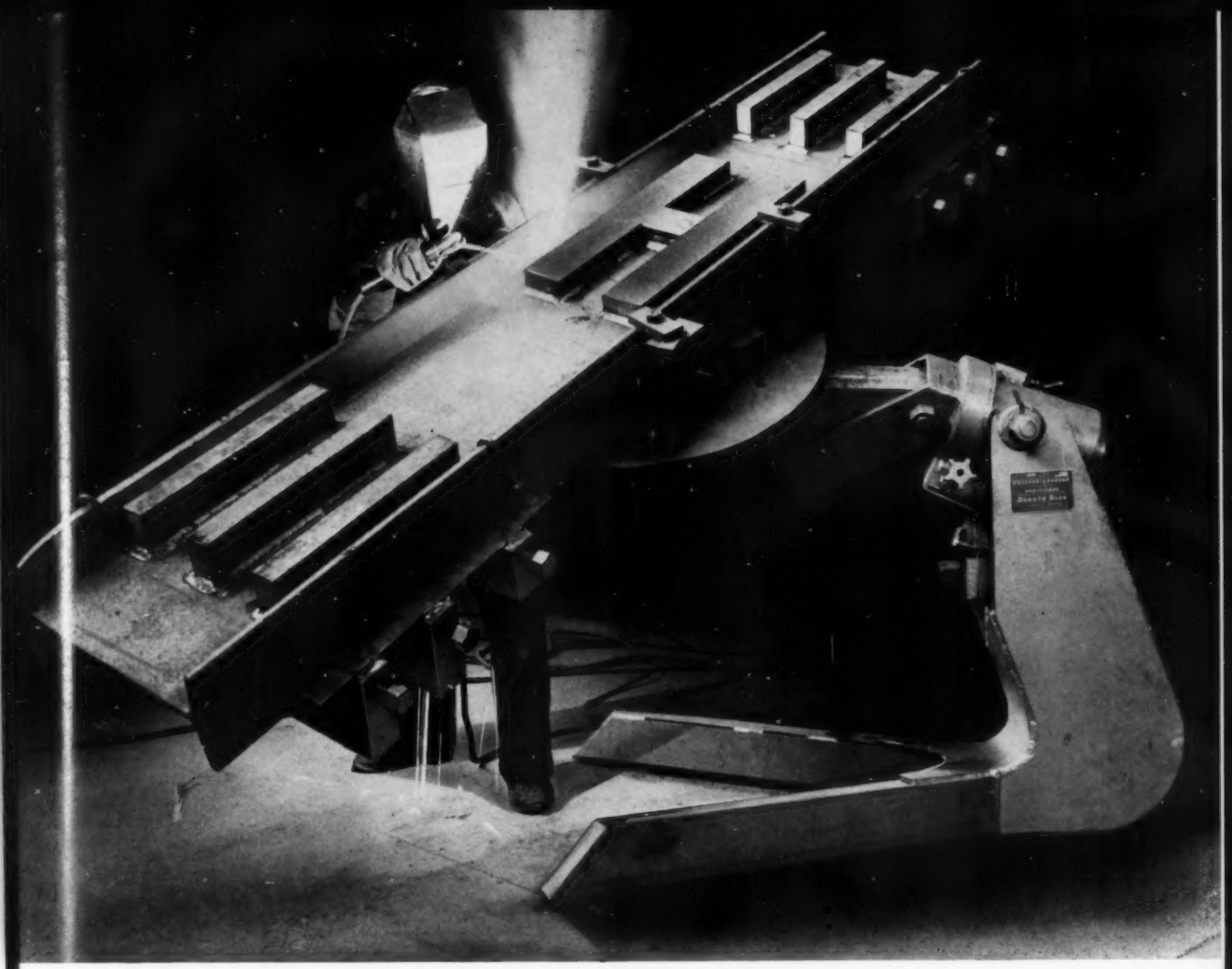

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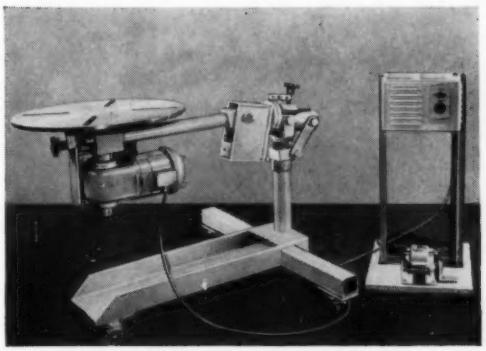

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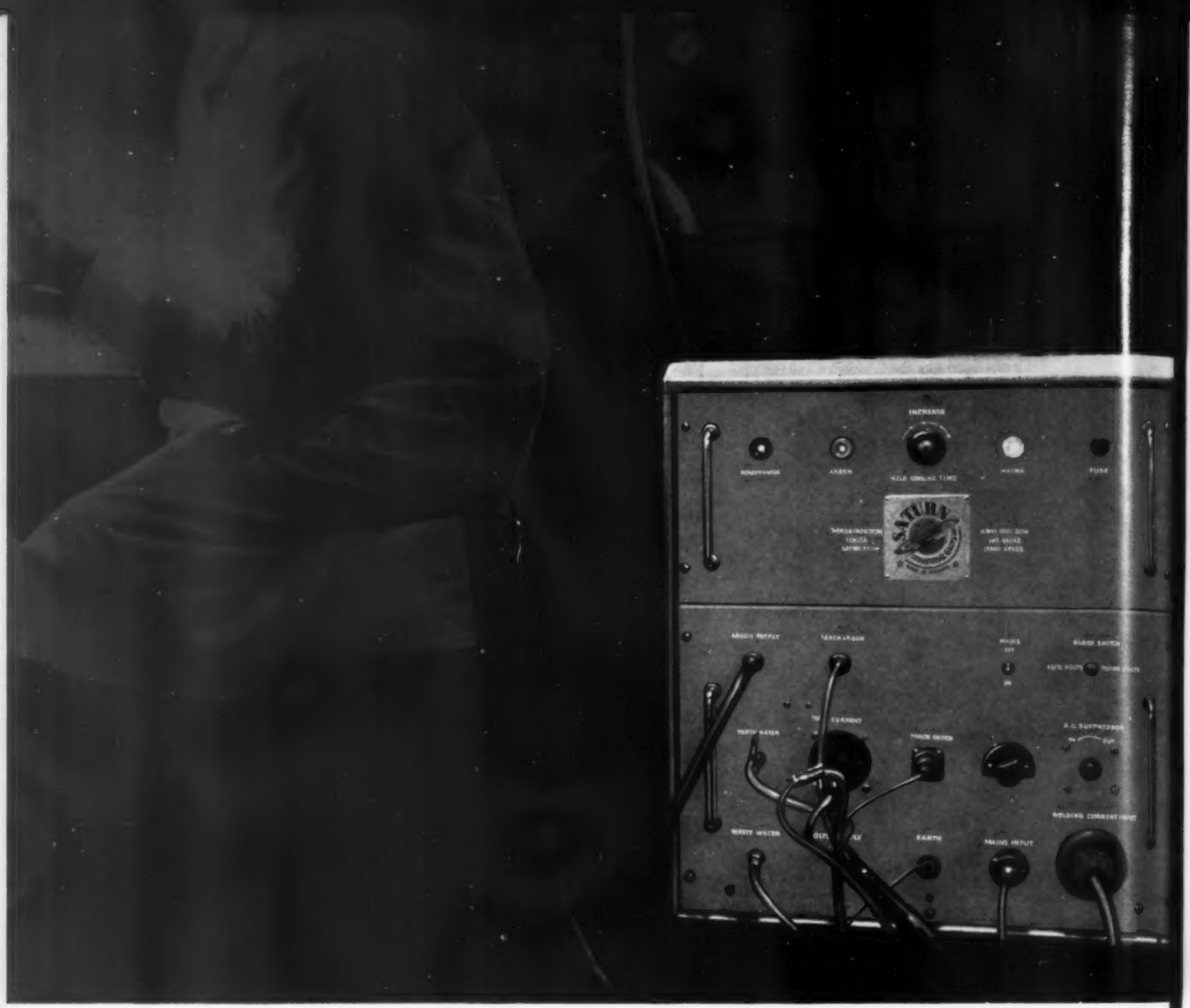

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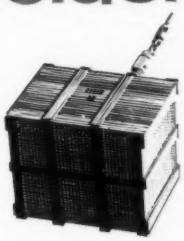

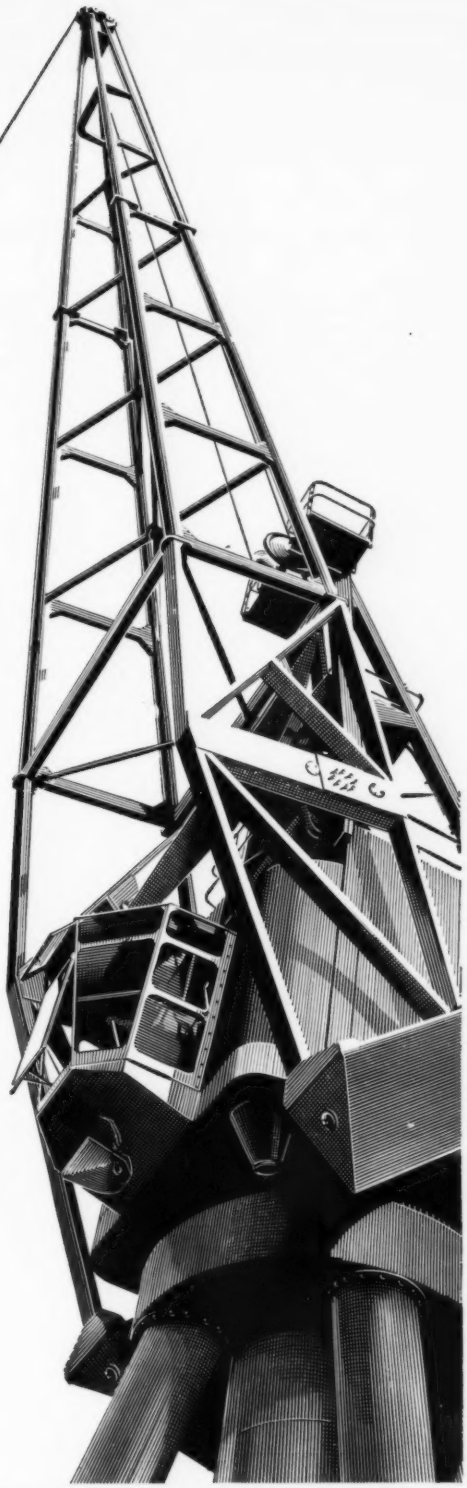

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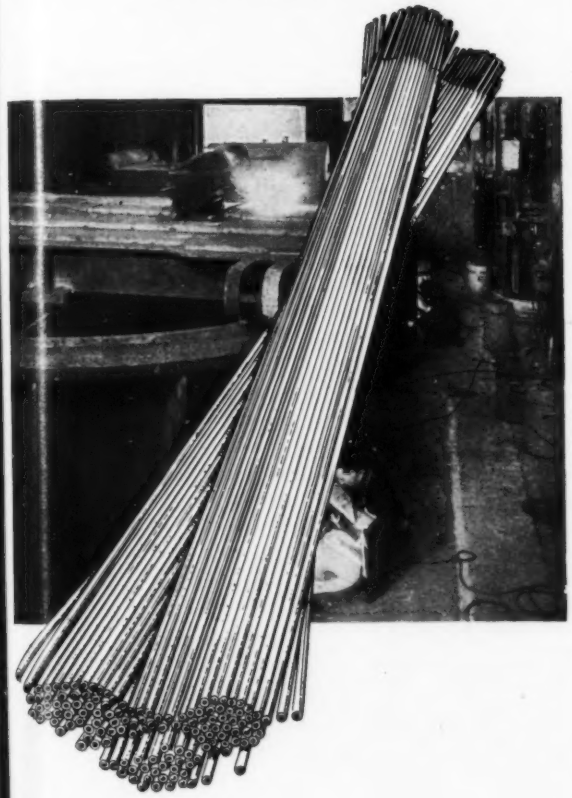

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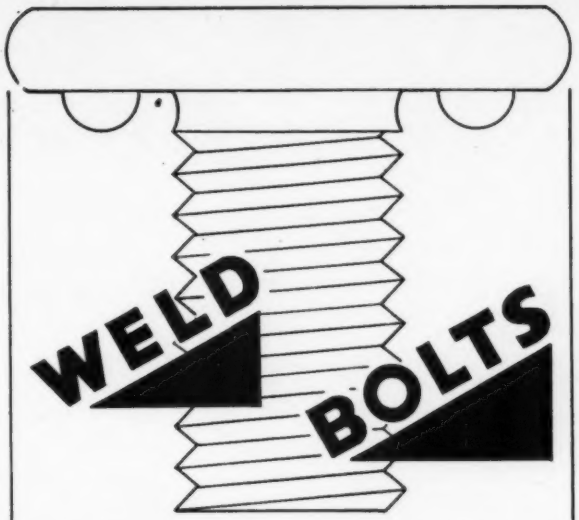

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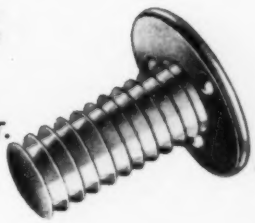

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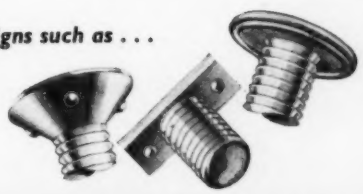

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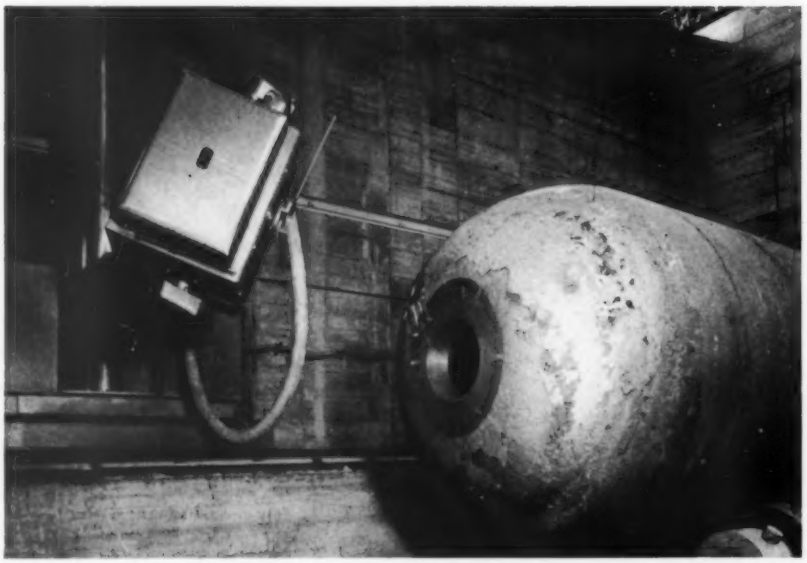

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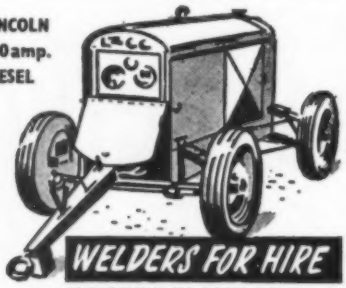

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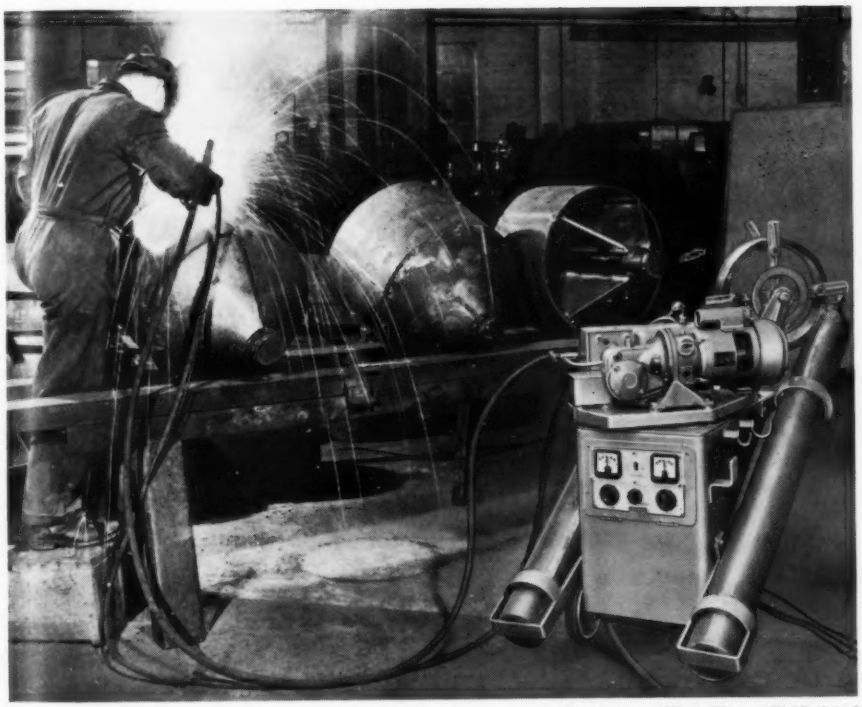

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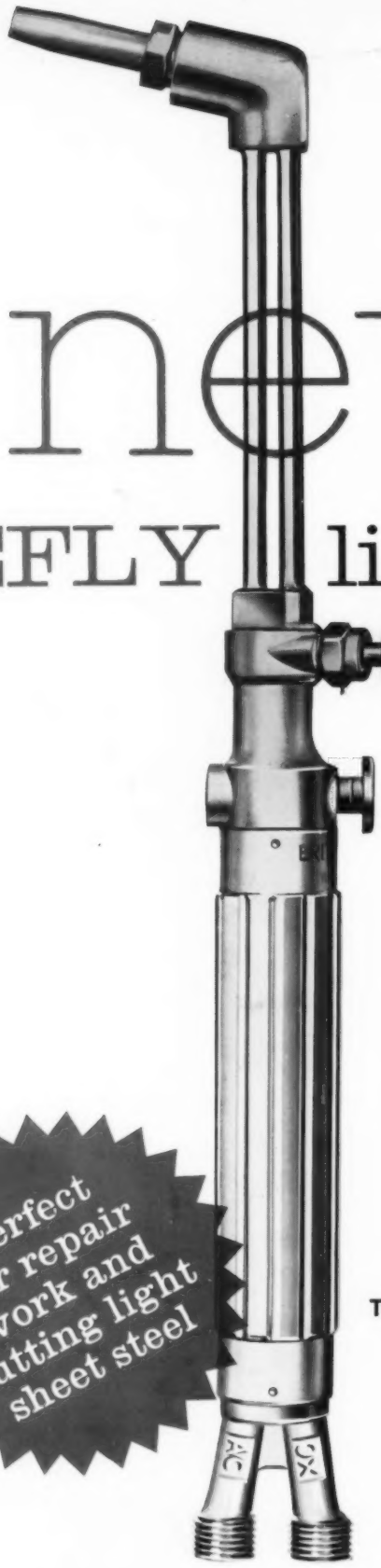

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